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TRANSIENT IONOSPHERIC ECHOES AT FIVE METRES WAVELENGTH

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Transient Ionospheric Echoes at Five Metres Wavelength

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Paragraph

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Operational Research Group (W. and E.) Report No. 348

Transient Ionospheric Echoes at Five Metres Wavelength

ABSTRACT

(i) An investigation of short duration radio echoes observed at 4 - 5 metres wavelength in the neighbourhood of the E region of the ionosphere is described. Observations by vertical beam radio equipments showed that the echoes occurred most frequently at a height of about 95 Km. Marked directional characteristics were revealed by the use of equipments with oblique beams, the diurnal variations being different on different bearings.

(ii) Analysis of the results has indicated the close link in characteristics of these echoes and meteors, and has thus confirmed the suggestion of meteoric origin which has been made by some previous workers. A detailed correlation is demonstrated in the present investigation, and a method is described for the determination of the radiants of the most active meteor streams by means of observation of these ionospheric echoes.

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HISTORICAL

1. The occurrence in the E region of the ionosphere of sporadic increases in ionisation, not explicable in terms of the normal E layer ionisation by ultra-violet light, was reported by Appleton (1) in 1930. This phenomenon has since been the subject of many investigations by radio pulse reflexion methods. The results have been described by Appleton and Naismith (2) who found that this abnormal E ionisation occurred as a thin layer at a lower height than the maximum of the normal E layer. The abnormal E layer might persist for minutes or hours, the critical frequency rarely exceeding 10 Mc/s and generally being considerably less. Some form of solar influence was found to be present, but the abnormal ionisation occurred at night as well as by day and it appeared that other agencies must be primarily responsible for its formation. The ionospheric studies at Tromsø by Appleton, Naismith and Ingram (3) indicated a relation between the development of the abnormal E layer and magnetic storms and aurora, and Berkner and Wells (4) found considerable latitude variations. Ratcliffe and White (5) reported a correlation with thunderstorms. Schafer and Goodall (6), in collaboration with Skellett (7), found that during the Leonid meteor showers of 1931 and 1932, the level of abnormal E layer ionisation reached its peak at the time of the expected maxima of the showers, and that increased ionisation occurred simultaneously with the visible passage of certain meteors. During Leonid showers in later years, Mitra, Syam, and Ghose (8), Bhar (9), and Pierce (10) reported some confirmation of the meteoric effects.

2. In addition to the abnormal (or sporadic) E layer, reflexions of duration varying from a fraction of a second to a few seconds have been detected at frequencies far exceeding the critical frequencies of either the abnormal or normal E layers. These echoes are now generally known as ionospheric scatter echoes. Their occurrence was noted by Appleton, Naismith, and Ingram (3), and their range distribution and reflexion coefficients discussed by Appleton and Piddington (11).

3. Eckersley (12) also described their characteristics, and Skellett (13) considered that the data accorded with the meteoric explanation. It may be noted that Schafer and Goodall (6) recorded these short duration echoes, in addition to the peaking of the abnormal E layer critical frequency, during the Leonid shower of 1931. Eckersley and Farmer (14) later investigated the direction of arrival and polarisation of the short scatter echoes and thought that the results did not conform with the meteoric hypothesis. Appleton in his recent Kelvin Lecture (15), considered however that the evidence so far available had strongly suggested meteoric origin.

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AIM OF THE INVESTIGATION

4. The present investigation, which commenced in October, 1944, was designed to elucidate further the properties and origin of the short scatter echoes by observations at frequencies around 70 Mc/s; such frequencies greatly exceed the critical values for reflexion from either normal or abnormal E layers. In fulfilling this plan, we have also been led to consider the possible relation between these scatter clouds of ionisation and the abnormal E layer. Many of the points raised in the papers briefly mentioned above will be discussed more fully in connection with our findings.

5. In Part I of the paper the investigation is described in chronological order. This enables the progress of the research to be seen in its proper perspective since the experimental plan was influenced very considerably by the reduction of available assistance from Service personnel after July, 1945.

6. Part II contains a general discussion of the data and conclusions.

PART I: EXPERIMENTAL OBSERVATIONS

INITIAL OBSERVATIONS, OCTOBER - NOVEMBER, 1944

7. Transient echoes were observed at wavelengths of 4 to 5 metres on certain long range Army radar equipments with elevated beams during the latter part of 1944. A chain of 12 of these radar sets was deployed and manned by A.A. Command, and the authors were directly concerned in an advisory capacity, both in the planning of the system and investigation of its operational performance. The transmitters each radiated approximately 500 pulses per second with a pulse duration of about 3 microsecs, and a peak power of 150 KW. The aerial systems provided beams with axes around 45° to 55° elevation, some of the equipments having stacks of four dipoles and other single Yagi aerials. The receiver time base extended to 150,000 yds., and the characteristics of all echoes exceeding 2 seconds duration were noted by direct visual observation.

8. An analysis of transient echoes observed between 16 October and 19 November, was made by E.D. Britton,* who was working in collaboration with the authors. The analysis showed that of a total of 348 echoes during the period 16 October to 19 November, the average duration was about 13 secs. The mean signal to noise-ratio was about 4, the peak values in amplitude being obtained at the onset of the echo. The average initial range was about 124 Km. Assuming the mean elevation of observation was that of the elevation of the maximum of the radio beam, the mean heights were calculated to be approximately 93 Km. for first appearance and 91 Km. for final range on disappearance. The analysis also revealed the interesting feature that although there was a considerable overlap in the coverage of the stations it was rare for an echo to be observed simultaneously by more than one station. Further, a diurnal variation in frequency of occurrence was recorded, the maximum being around sunrise, the minimum after sunset.

INVESTIGATIONS DURING JUNE - OCTOBER 1945

9. The above series of observations was incidental to an operational watch maintained for other purposes. At the end of the war it became possible through the co-operation of A.A. Command to utilise their Army radar facilities for experiments designed to elucidate more specifically the characteristics of these short echoes, and hence to add to the existing knowledge concerning their nature and possible origin. To this end, a watch was set up involving five radar stations, manned and organised by A.A. Command, while the authors were responsible for scientific direction of the experiments and analysis of results. There were two systems, illustrated in Fig. 1, which consisted of:-

(a) Two similar sets A1 and A2 at Aldeburgh having twin vertical Yagis on the receivers and single Yagis on the transmitters. These equipments were in operation at Aldeburgh during June and July, 1945, and later were transferred to Sheerness where a further set of recordings was made from 3-13 October, 1945.

(b) Three similar sets, B1, B2 and B3, at Aldeburgh, Walmer, and Richmond respectively, having twin Yagis on the receivers, and single Yagis on the transmitters, the angle of elevation of the Yagi axes being 52° in each case. The bearings were initially chosen so that the beams of the stations intersected at a point about 100 Km. in height and approximately equidistant from each station. Subsequently observations were also made on other bearings. The three sets were operated during June and July, 1945.

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* The analysis was described in A.O.R.G. Memo. No. 462.

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10. The polar diagrams of these sets, obtained by measurements with a small C.W. oscillator suspended from a balloon, are shown in Fig. 2. We shall now proceed to describe the purpose of the two systems and the results obtained from them in the order mentioned.

The vertical beam stations, A1, A2.

11. It was considered that amongst other characteristics which might emerge from their use, the vertical looking sets would be especially valuable in determining height distribution. The purpose in having two stations was to compare their performance both with similar and varied conditions of operation. In the first few weeks they were operated independently at frequencies of 73 Mc/s and 55 Mc/s; but subsequently both were maintained at 73 Mc/s and the effects of varying polarisation, and of using a common transmitter instead of two independent ones were investigated.

12. A comparison was also made between visual recording of echoes displayed on the cathode ray tube as deflections of a linear time base, and photographic recording of a brightness modulated time base on a 16 mm. film moving at a speed of 1.2 inches per minute. In the latter case echoes were recorded on the film as spots if the echo duration was short, or as lines if the duration was long enough for the film to have moved appreciably. Cine photographs, taken at 16 frames a second of typical echoes presented as deflections on a linear time base are shown in Fig. 3 a, b, c, d. These illustrate the appearance of the time base to the operator making visual observations. An example of an echo of very short duration, in this case of large amplitude, is given in Fig. 3 b, in which the echo can be seen during only one frame, and its duration must hence be about 1/16 second or less. Typical scatter echoes shown by photograph recording of the brightness modulated trace are given in Fig. 4, which includes examples of echoes lasting several seconds.

13. We shall first consider the results for the following three periods, for each of which the total number of echoes observed visually exceeded 1000.

Period	Details
22 - 29 June	A1 on 73 Mc/s, A2 on 55 Mc/s. Visual Recording.
7 - 17 July	A1 and A2 on 73 Mc/s, with common transmitter. Visual and Photographic Recording.
24 July - 1 Aug.	A1 and A2 on 73 Mc/s, with separate transmitters. Visual and Photographic Recording.

14. Graphs showing how the number of echoes per hour varied with the hour of the day are given in Fig. 5, and the range distributions shown in Fig. 6. These graphs of visual recordings demonstrate substantial agreement between the two stations, although the hourly rate for the 55 Mc/s station, A2, in the first period is higher than that of the 73 Mc/s station A1. Certain differences between the three periods are apparent in the mean diurnal variations of rate of occurrence, most particularly, the pronounced peak in frequency which occurs around midnight in the third period; the interpretation of this peak is discussed in Part II of the report. The range distributions show no marked changes for the three periods. Since the radio beam axis is vertical, these

approximately represent height distributions, and the region in which the maximum number of echoes occur is around 97 Km. for each period. The small correction to the range distribution, to take into account the finite beamwidth, is also considered in Part II.

15. Despite the fact that the two sets were on the same site with almost identical radar coverage, and that the form of the results reveals general similarity, the number of simultaneous observations recorded visually at the two stations amounted to slightly under 50% of the echoes seen by any one station. This is readily explicable from the fact that by far the greater number of echoes of echoes were of momentary duration and that echoes of small signal strength were more numerous than those of large amplitude. As an example, the ratio of numbers of echoes of duration less than 1 second compared with those of greater duration, was 3.4 : 1, while the ratio of the number of signals exceeding twice noise power compared with those exceeding four times noise power was 2.2:1. It is understandable therefore that visual observation might be especially liable to miss a proportion of echoes owing to preponderance of echoes of short duration and small signal amplitude.

16. Operation of the photographic recording of the brightness modulated time-base was intermittent owing to the development of technical faults, but the results indicated an increase of about 20% in the total number of incidents and a slight increase in the number of coincidences. The efficiency of this system depended on careful adjustment and stability in the setting of trace brightness and of receiver gain, which determined the noise level which appears as a speckled background on the film. Imperfections in the recording apparatus prevented the coincidence rate from being greater, but it must be remembered that the difficulties of recognising small, short duration echoes on a noise background is such that 100% coincidences can never be expected. With the knowledge of the earlier experiences, special precautions were taken in a few days of photographic recordings obtained at Sheerness in early October, 1945, and the coincidence rate then rose to 85%.

17. In addition to the three periods of observation tabulated above, several experiments on polarisation effects were undertaken for periods of one or two days. Although these tests covered such a limited period, they were sufficient for the conclusion to be drawn that there was no significant change when the plane of polarisation was changed through 90°, that is from East - West to North - South. Further, when the polarisation of a transmitter was at 90° to that of the receiver the number of echoes fell considerably, showing that the polarisation of the echoed field tended to be the same as that transmitted.

The inclined beam stations

18. We shall now consider the results for the three sets B1, B2, and B3, at Aldeburgh, Walmer, and Richmond respectively, with the axes of their inclined beams intersecting at about 100 Km. height. The purpose of this experiment was firstly, to fix the location in space of echoes seen simultaneously by the three stations by measurement of the ranges from the three observing stations, and secondly, to investigate any aspect effects, that is variation of reflected signal according to the direction of incidence of the radio waves. It was realised that both of these aims might not be fulfilled, since, if aspect proved a critical factor, the chances of simultaneous observation of echoes by the three stations would be diminished. In later periods the three stations were set on other bearings in order to compare the results for several directions, the axes of the three beams in these cases no longer having a common point of intersection. Visual recording was used throughout,

with some additional checking of results by photographic recording. The experiments and the results obtained, for three periods tabulated below, will now be discussed.

Period	O.S. Grid Bearing of Stations
1 June - 17 July, 1945	B1 - 230°; B2 - 315°; B3 - 62° (Beam axes intersecting)
17 June - 26 July, 1945	B1 - 180°; B2 - 270°; B3 - 90°
26 July - 1 Aug., 1945	B1 - 180°; B2 - 0°; B3 - 90°

19. The first period when the three stations were set with their axes intersecting as illustrated in Fig. 1, extended from 1 June to 17 July, thus covering the first two periods for the vertical beam stations discussed in the previous section. Graphs of the variation of frequency of occurrence of echoes with time of day are shown in Fig. 7, and of the range distribution in Fig. 8. As compared with the vertical looking stations, the average number of echoes is seen to have increased and the range distribution extends to greater ranges. These facts may be interpreted by reference to the results for the vertical station which indicated a fairly narrow height band containing the sources of reflexion. The beams of the inclined stations intersect a greater area of this layer as illustrated in Fig. 9 and the number of echoes and the limits of maximum and minimum ranges are increased accordingly.

20. A more interesting feature, however, is presented by the marked maxima and minima in frequency of occurrence of echoes, the times of these maxima and minima being different for the three stations respectively. Thus B1 has its greatest peak in frequency at 2130 hrs., B2 at 0030 hrs., and B3 at 1230 hrs. This indicates at once that the sources of reflexion show marked aspect effects which are more apparent with inclined beams than with vertical.

21. Confirmatory evidence of the aspect sensitivity of the sources of reflexion was provided by the rarity of simultaneous echo observations by the three stations. In order to allow for lags in operators' recording, a time difference of up to 5 secs., was permitted in regarding echoes entered in the logs of the respective stations as simultaneous. Now in the period 1 June to 17 July, on only four occasions was this criterion satisfied out of an average of over two thousand echoes observed by each station when they were all in operation at the same time. If the stations are considered in pairs, the average percentage of incidents observed by two stations, with not more than 5 secs. interval between recorded times, was approximately 3% of the total number of echoes seen by one station. In order to appreciate the theoretical chances of such coincidences, we must consider the extent of overlapping coverage. (See Fig. 9.)

22. The probability of coincidences in different cases has been calculated assuming isotropic scattering sources in a single thin layer at 97 Km. height, and echo strengths as observed by the vertical beam stations. The percentage coincidences calculated on this basis are compared below with the observed results for visual recordings.

Triple coincidences for B1, B2, B3:-

Calculated probability = 3.1% of total number of echoes seen by all stations.

Observed coincidences = 0.02%.

Double coincidences, B1, B3:-

Calculated probability = 10.5% of total number of echoes seen by both stations.

Observed coincidences = 1.6%.

23. Thus we see that even if we multiply the observed coincidences by a factor of 4 in the case of double coincidences and of 12 in the case of triple coincidences in order to allow for echoes missed by the observers, the calculated probability, based on the assumption of isotropic scattering sources, is greater than the observed percentage. We may therefore conclude that the echoes show differential effects according to the direction of the observation. This is further borne out by the coincidence percentage observed between B1, the oblique beam station at Aldeburgh, and the vertical beam station A1, (or A2), situated on the same site. If the echoing sources are sensitive to the direction of incidence then the probability of coincidence between B1 and A1 (or A2) might be increased over that calculated on the basis of isotropic sources. This is actually the case as shown by the following figures.

Double coincidences B1 and A1 (or A2).

Calculated probability = 1.2% of all the echoes seen by both stations. (This figure is more liable to error than those quoted above owing to incomplete knowledge of the beam of the inclined station in the vertical direction.)

Observed coincidences = 3%

This difference is accentuated by allowing for visual echoes missed. We conclude therefore that both the reduction of coincidences for stations on separated sites but with intersecting beams, and the increase for stations on the same site with partial overlap of coverage, as compared with the calculated values, accord with the assumption that the echo sources are sensitive with respect to aspect.

THE METEORIC THEORY

24. At the end of July, A.A. Command were unable to continue to provide the personnel to man the five stations. Their participation ceased, therefore, except for some further valuable assistance in the reading of the photographically recorded films and for the further trial in October with the vertical beam sets at Sheerness which has been discussed previously. The research was therefore continued on a more limited scale in Richmond Park by the authors, with the help of a few other Operational Research Group personnel.

25. At this time it was felt that the results presented strong confirmation of the meteoric origin of the echoes. Meteors are known to leave streaks or trains which can persist for long periods. Such glowing columns must evidently be intensely ionised and the high electron densities will therefore produce totally reflecting surfaces for frequencies below the critical frequency, while partial reflexions will occur at higher frequencies.

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Their mean height, derived from astronomical observations, corresponds closely to that indicated by the range distribution for the vertical stations. (Fig. 6). Further, since a cylindrical column presents its most favourable aspect for a reflexion back when its axis is at right angles to the incident ray, we have at once a possible explanation of the critical aspect effect just discussed, and the reason why the range of an echo generally remains nearly constant, namely that the column is usually only sufficiently reflecting to be observable only from the side view. A diurnal variation, as shown in Fig. 7, would be expected from the daily cycle of changes in bearing and elevation of the meteor radiants active at the time.

26. Further in October and November, 1944, when the first observations were made, many echoes were of long duration. Only echoes of more than 2 secs. duration were noted, and of these the average duration was 13 secs. In June and July 1945 there were none of even 13 secs. It was felt that this might accord with the meteoric theory since the second half of the year is well known to be more favourable than the first for meteor observation.

27. The detailed discussion of these points will be left to Part II of this paper. For the present it will suffice to say that the evidence in favour of meteoric origin of the echoes appeared strong. The subsequent investigations therefore were directed so that, with the limited facilities which remained available after the end of July, some clear correlation with a meteor shower might be sought.

OBSERVATIONS DURING THE PERSEID SHOWER, 1945

28. The first attempt to determine specific changes in scatter observations during one of the more notable meteor showers of the year was made during the Perseid shower of August, 1945. The set, E3, was still available in Richmond Park, and the watch was carried out, from 0930 to 1230 hrs. G.M.T. daily from 10 - 14 August inclusive. The set was maintained on a bearing 90° throughout. The Perseid radiant is R.A. 48°, Decl. + 58° and the shower normally reaches its peak on 11 - 12 August. As observed from Richmond Park the radiant should move from bearing 300° to 320° and the elevation from 60° to 40° during the time of the watch. From the polar diagram of the equipment shown in Fig. 2, and the range limits of observation, in this case from 80 Km. to 200 Km., it may readily be deduced that the beam of the set just covers directions at right angles to the radiant during the period of the watch. The authors are indebted to B. Rimmington for valuable assistance in carrying out the photographic recording and subsequent reading of the film.

29. One of the most striking results which emerged was the increased duration of the echoes, as compared with those of the previous months. The number of echoes of long duration rose to a pronounced peak on 12 August, when 24% of the echoes persisted more than 5 secs. This may be compared with the last week of July when less than 2% of the echoes were of more than 5 secs. duration. The frequency of occurrence of the echoes reached its maximum on 11 August. These two results are represented graphically in Fig. 10, and for comparison, we have included those obtained during 26 - 31 July for the same daily period, set bearing, and recording method. The peak in the frequency of occurrence of echoes of more than 5 secs. duration is particularly marked. Although no direct visual observations of the meteor shower was attempted, it is known that the Perseids appear with no remarkable variations in numbers practically every August. The stream begins to cut the earth about the middle of July, the maximum may be expected on 11 August. Meteors are still very frequent for the next two nights after which there is a sharp decline (16). The observations therefore correspond well with the known astronomical characteristics.

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THE INVESTIGATIONS OF DECEMBER, 1945 - JUNE, 1946

30. It was not practicable, owing to staffing problems, to continue the scatter watch further until early December, 1945. It was resumed at that date with a single vertical beam station in Richmond Park, the plan being to investigate over a long period any correlation between frequency of occurrence of echoes and meteor showers. It was felt that for this purpose the vertical set would present the simplest conditions of watch, the diurnal variations being much less marked than with oblique beams. Further, it would provide an accurate height record. Owing to staff limitations, the watch was kept only between 0915 - 1200 hrs. and 1400 - 1630 hrs. G.M.T. daily; these daily observations were made over a period December 1945 to June 1946 inclusive. All recording was made by visual observation of the echoes on the cathode ray tube. During the period 20 - 22 April inclusive, the time of the Lyrid shower, the watch was carried out at night along with a visual watch for meteors in the sky. Daily measurements of transmitter field strength and receiver sensitivity were made so as to exclude equipment performance as a possible variable affecting the observed rate of occurrence of echoes.

Record of mean hourly rate, December, 1945 - June, 1946.

31. The main purpose of this investigation was as mentioned above, to look for clear correlations of the hourly rate with main showers. Referring to the Meteor Diary given by J.P.M. Prentice in the British Astronomical Association Handbooks for 1945 and 1946, we see that the main showers expected during the period are the Quadrantids on 2 - 3 January, and the Lyrids, on 20 - 22 April. The Quadrantids should be characterised by a duration of about 24 hours. The Lyrids, on the other hand, have a duration of a few days with an expected maximum on 21 April. In Fig. 11, where the mean hourly rate of all echoes is plotted for the period 6 December - 26 May, we see at once that peaks occur at the expected times for these two showers. A prominent peak for a single day occurs at the time of the Quadrantid shower, while a marked broader peak with a maximum on 21 April occurs at the time of the Lyrids. This faithful reproduction of the meteor characteristics in the hourly rate of scatter echoes provided us with unmistakeable evidence of the meteoric origin of at least a major proportion of these echoes.

Simultaneous echo observation and visual meteor watch, 20 - 22 April, 1946.

32. A direct watch for meteors in the sky during the time of the Lyrid shower provided further verification that scatter echoes are associated with meteors. These observations were made during 2030 - 2400 hrs. G.M.T. on each of the nights of 20 - 22 April. The sky was observed visually through a horizontal rectangular frame in a celluloid screen vertically above the observer. The angular subtension of the aperture roughly corresponded with the radar beam coverage so that the field of view included most of the region in which a good radar response from an echoing source might be expected. As the screen was not opaque it was possible to see a considerable region of the sky outside the rectangular frame although not to give it detailed attention. The screen was divided into zones and provided with white clock-hour markings enabling the apparent track of a meteor to be described approximately; the markings were illuminated with a diffused dim red light to render them visible while not noticeably impairing dark - adapted vision. The radar observer and the meteor "spotter" gave warning by means of buzzers to recorders who noted the times to the nearest second. Further details were subsequently passed by telephone.

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METEORS				RADAR ECHOES				
No.	Date in April 1946	Time B.S.T.	Tracks passing through frame	Time B.S.T.	Duration Seconds	Range Kms.	Signal / Noise	Details of wide echoes
1	21	21.50.01	Yes	21.50.01	M	98	$1\frac{1}{2}$	-
2	21	21.59.20	Yes	21.59.20	3	121	Saturation	Beating, 3 Km. broad
3	21	22.57.00	No	....	....	No echo	seen	....
4	21	22.59.28	Yes	....	....	No echo	seen	....
5	21	23.27.51	Yes	23.27.53	M	112	$1\frac{1}{2}$	-
6	21	23.31.21	No	....	....	No echo	seen	....
7	21	23.32.39	Yes	23.32.40	1	113 - 116	$1\frac{1}{2}$	3 peaks, moving outwards
8	22	00.39.43	Yes	00.39.51	M	98	$1\frac{1}{2}$	-
9	22	00.45.00	No	....	....	No echo	seen	....
10	22	23.08.03	Yes	23.08.05	$\frac{1}{2}$	107	2	2 Km. broad
11	22	23.23.34	No	....	....	No echo	seen	....
12	22	23.40.27	No	23.40.27	M	102	5	2 Km. broad
13	23	00.31.48	Yes	00.31.51	M	106	2	-

(M = Momentary, duration less than $\frac{1}{2}$ sec.)

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33. The sky was clear throughout the whole period of observation, with the exception of about twenty minutes on the second night when a filmy and broken patch of cirro-stratus entered the field of view, but this was not sufficiently dense to impair observation seriously. The apparent tracks of all the meteors seen, projected on to a horizontal plane, are shown in Fig. 13. The list of meteors, 13 in all, and particulars of the radar echoes are given in the table on the previous page.

34. In the preceding table there were 8 meteors whose tracks, produced if necessary, passed through the region of the viewing frame, and of these, 7 were associated with radar echoes. As to the remaining one, the observer stated at the time that ~~he was~~ doubtful whether he had genuinely seen a meteor; it is notable that all the others were stated to be bright and unmistakeable. The visible parts of the paths of three of the meteors, which gave radar echoes, were completely outside the frame, but in two cases the produced paths passed through it.

35. We may conclude that visible meteors entering the radar coverage can definitely be associated with scatter echoes. In addition to the radar echoes listed in the above table, there were about seven times as many radar echoes with no meteors apparent in the sky. The existence of faint meteors which are observable telescopically although not visible to the unaided eye is well-known to astronomers. The large number of scatter echoes with no apparent visible meteor is therefore a result to be expected. Another approach to this problem is to consider whether the characteristics of the scatter echoes would lead one to group the echoes into one class, with properties corresponding closely with those of meteors. This is indicated in one way by the correlations in hourly rate just considered. The general comparison of the properties of the scatter echoes with those of meteors is dealt with more fully in Part II of this paper.

PART II: DISCUSSION AND CONCLUSIONS

36. The most important outcome of the investigations described in Part I was the conclusion that at least a large proportion of the ionospheric scatter echoes are caused by meteors. Skellett (7) (13), first suggested that the ionisation caused by meteoric impact with the molecules in the upper atmosphere was the probable source of the abnormal E and short scatter echoes. Trowbridge (17) had pointed out earlier the similarity between the visible radiation from meteor trains or streaks*, which may persist many minutes, and the afterglow produced by electrical discharge in gases, which thus indicated that ionisation had occurred. In their theoretical work, Lindemann and Dobson (18), Sparrow (19), and Maris (20) all agreed that ionisation would result from the impact between meteors and the molecules of the upper atmosphere. We shall now proceed to review the data from all the experiments, formulating the ionospheric scatter echo characteristics more precisely and discussing in further detail the extent to which their properties conform to the meteoric explanation. We shall also consider the relation of the short scatter echoes to the abnormal E and other ionospheric layers.

HEIGHT DISTRIBUTION OF SCATTER ECHOES

37. We have already seen in Fig. 3 that the range distribution of the echoes as measured by the vertical stations, remained substantially the same for three separate periods during June and July, 1945. A diurnal variation in range is discernible, however, as shown in Fig. 14. For each hour of the day the aggregate range distribution was found over the period June and July, 1945. When the values were graphed and a smooth curve drawn, the ranges at which the maximum number of echoes occur could be assessed for each hour of the day. These peak ranges, plotted in Fig. 14, show a diurnal variation of approximately 3 Km., the maximum height being reached shortly after noon.

38. In Fig. 15, the mean range distribution is drawn for four successive periods from December, 1945 to June, 1946. There are some changes both in the width of the distribution and its maximum height, but the evidence is not sufficient for any firm conclusions to be drawn concerning seasonal variations. In general we may say that the maximum of the range distribution shows a high degree of constancy, the height generally being about 97 Kms., as indicated by the results during June and July, 1945 (Part I, Fig. 4), and December - June (inclusive), 1946. Only the June, 1946 results show a slight variation, of about ± 3 Km., but this group contains a smaller number of echoes since it covers a period of less than one month.

39. In Fig. 16 is plotted the range distribution of all echoes observed in June and July, 1945, by the vertical beam stations, A1 and A2, and through it a smooth curve has been drawn. Now in order to convert this into a true height distribution we must allow for the spread in range which results from the finite width of the radar beam. Suppose, for example, all echoes occurred at a fixed height of 100 Km. Owing to the width of the radar beam, the distribution would have an abrupt near edge and then trail as illustrated in Fig. 17. The following method, as illustrated in Fig. 18, was adopted to correct this effect. The observed range distribution was taken as a first assumed true height distribution, which we will call distribution 'A'. When the effect of the finite beam

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* A distinction between streaks and trains was made by Herschel (21) who termed the luminous column of glowing gas "streak" and reserved the word "train" for the spark-like emissions associated with certain meteors. Many writers, e.g., Olivier (16), refer to the glowing column as a "train" or "streak", a convention which is followed here.

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is applied we obtain a new distribution, 'B'. A distribution 'C', determined by $AC = B^2$, was then deduced and used as the new assumed distribution for continuing the method by successive approximations. The solution obtained is shown in Fig. 19, the maximum being about 95 Km., and 90% of all the echoes being contained in a layer extending from 87.5 to 107.5 Km. As mentioned in Part I, this layer corresponds well with the normal observed heights of meteors and their trains. Denning (22) concluded that, in general, meteors appear at about 76 miles (approx. 122 Km.) and disappear at about 51 miles (approx. 82 Km.) Trowbridge (17) computed that the mean height of trains was 87 Km., the limits for appearance and disappearance being 103 Km. and 70 Km. respectively.

40. It has been known from the earliest observations of the short scatter echoes that they are roughly situated in the E region of the ionosphere. It is therefore of interest to consider to what extent the height of maximum occurence is related to the heights of the maximum ionisation density of normal or abnormal E layers. Now Appleton and Naismith (2) found that the mean heights of the maximum ionisation level for the normal E were 120 and 134 Km. for summer and winter respectively, while for the abnormal E they were 113 and 130 Km. respectively. Since the region of maximum frequency of occurence of the scatter echoes is around 95 Km. we conclude that it is not related in height to the E layers. Accepting the theory that the meteor can, by virtue of its high velocity, produce a highly ionised column of gas, we may infer that the meteor itself is the main ionising agency and that in this region the atmospheric conditions are appropriate for ionisation to occur in this way. No permanent condition of ionisation need be assumed and if E layer ionisation is a factor, it has only a minor effect. This is not surprising since the frequencies used in the present investigation are of the order of 10 times the critical frequencies for the normal or abnormal E layers. This implies that we are concerned with regions with electron densities of the order of 100 times that of the E layers. We thus prefer to consider the region as a separate one and we may refer to it as the 'meteoric layer'. It will be seen that the shape of the height curve (Fig 19) approximates in characteristics to a Chapman region, which might be expected for ionisation produced by an external agency of this nature even though the ionisation is only of transient duration.

41. It is of interest to determine whether the range distributions are the same for scatter echoes of different characteristics in duration or complexity. In Fig. 20 the range distribution for 'momentary echoes', (duration less than ½ sec.) is compared with that of echoes of longer duration, and that for echoes of complex appearance with that for single echoes. In both cases we see that longer duration echoes and complex ones show a range coverage extending to slightly greater heights. Variations in meteors, such as size, velocity, fragmentation, etc., are assumed to be the controlling factors. Meteors of greater speed might be expected to produce ionisation at greater heights where the rate of ionic recombination is slower due to reduced pressure and the echoes consequently of longer duration. It does not appear justifiable to postulate origins of a different nature according to the echo characteristics, particularly as the differences in range distribution are small. Further support for this view is afforded by the determination of correlation coefficients for the following entities:-

Entities		Period for Analysis	Correlation Co-efficient
(a)	(b)		
Momentary echoes	Longer duration echoes	30 days, by days	0.67
Single echoes	Complex echoes (Multiple or broad)	30 days, by days	0.56
(No correlation was found between complex echoes and long duration echoes.)			

MOTION OF SCATTER ECHOES

42. The majority of the echoes appear stationary in range; approximately 2% show a movement in range. This change is most clearly detected in the case of the long duration echoes (15% of echoes of duration exceeding 1 sec. show a movement) and the mean rate can be deduced with reasonable accuracy. These results are illustrated in Fig. 24. The velocities are not, in general, sufficient for the movement to be explained by the velocity of the meteor itself. If the ionised column produced by the meteor is the source of the scatter echo we should expect the maximum echo from the broadside-on view, and if the train size remained constant and its position did not drift, the range would remain constant. One cause of the average reduction of range may well be the lateral expansion of the ionised column. Trowbridge (17) noted that the average rate of diffusion appeared to be about 0.002 Km. per second for periods of observation of the order of 10 minutes, but the rates were considered to be much greater immediately after formation of the train. If the rates in the first few seconds are of the order of 1000 times greater this effect might well account for the trend towards reduced range.

43. Drifts and distortion of the train, or streak, present another factor which can cause range movements. Visual observations by Olivier (23), and others, have demonstrated that the winds in different strata show both different velocities and different directions. These velocities are generally of the order of 0.05 Km. per sec., but the apparent rate of movement resulting from the shifting of the point of reflection on the distorted train might be much greater.

44. In this connection we may refer to Eckersley and Farmer (24), who considered the meteoric explanation unlikely from their observations showing that when a scatter echo is produced a 'mirror' type reflexion occurs, while after a few seconds there appears to be a number of widely spaced centres. This result, however, might well be expected from meteor trains, which are at first comparatively straight and then become distorted. Trowbridge (17) quotes the following description of an observer's report of a meteor train, or streak ... "It appeared very bright and unbroken, straight as a shaft, clean and sharp in outline,..... but in two seconds, it became crooked and sinuous."

45. The observation of 'whistles' in receivers tuned to carriers of short wave transmitters was made by Chamanlal and Venkataraman (25), who also reported some coincidences with visually observed meteors. These 'whistles' were assumed to be due to the Doppler effect arising from the relative movement of the meteor itself. This apparent discrepancy with our own findings, that the majority of echoes seen show no range movement, and our consequent assumption that the echoes are broadside

reflexions from the trains or streaks, requires explanation. We can, however, suggest tentatively the following possibilities; (a) the echo from the head of the ionised column may be more readily detectable around 7 Mc/s, the radio frequency of the Indian observations, than at our radio frequency of about 70 Mc/s, and a continuous note presented aurally in any case provides a more sensitive means of detection than the visual presentation of a pulse on a cathode ray tube; (b) the meteoric 'whistles' may be in fact caused by the lateral expansion of the meteor streak or train; (c) that some of our observations of echoes moving in range (see Fig. 21) represent actual movement of the head of the ionised column, but that in general such echoes are missed in comparison with the stronger and more enduring reflexions from the columns viewed from the side.

46. Chamanlal and Venkataraman found that when E layer returns were obtained by pulse reflexion methods on 7 Mc/s, they appeared to follow the passage of a meteor as indicated by a whistle in a receiver tuned to a C.W. transmitter on a slightly different frequency. They considered this to be explained by the settling into a stratified layer of the ionisation produced by the passage of the meteor. On a few occasions only they noticed a weak pulse return with rapidly decreasing range occurring simultaneously with a strong Doppler whistle. In our view the most likely explanation is that the ionised air at the head of the meteor is generally missed by pulse reflexion methods because of the weak amplitude of the echo, the C.W. method with aural presentation of the Doppler note being more sensitive; further, the subsequent stationary pulse reflexion echo is from the meteor train which cannot appear until the train has reached approximately the point of intersection of the normal from the observing station to the line of travel of the meteor.

SIGNAL STRENGTH DISTRIBUTION

47. We will now consider the signal strengths of the echoes and derive a figure for the mean equivalent echoing area. The operator estimated the maximum amplitude reached by the echo pulse seen on the tube face. (This maximum appears to be attained rapidly on first appearance.) The receiver display is known to give approximate proportionality between echo height and the peak echo power. Fig. 22 shows the observed distribution of echo amplitudes and hence of echo powers, in relation to the noise level. Owing to the liability of error in the operator's estimation of very low signal amplitudes we have considered only the cases where the ratio of signal power to mean noise power exceeds 1.25, and have therefore taken this as our lower limit of observation. The true distribution of echoing areas is modified, as regards the received power distribution, by the form of the radar beam, in which the sensitivity decreases progressively in regions further and further from the axis.

48. It was found that a reasonable agreement with the observed signal strength distribution was obtained in the following assumption. The elementary probability δp that an echo will have a (maximum) equivalent echoing area between the limits A and $A + \delta A$ was taken to be of the form

$$\delta p = C e^{-A/K} . \delta A \quad \text{where } C \text{ and } K \text{ are constants.}$$

Since $\int_{A=0}^{A=\infty} \delta p = 1$, we derive at once that $C = 1/K$.

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Further, the mean echoing area $\bar{A}$ is given by

$$\bar{A} = \int_{A=0}^{A=\infty} A \cdot dp = \int_0^{\infty} \frac{A}{K} \cdot e^{-A/K} \cdot dA = K$$

whence we may write

$$\delta p = \frac{1}{\bar{A}} \cdot e^{-A/\bar{A}} \cdot \delta A$$

From the foregoing it may readily be shown that, of a large number N of echoing sources, the number with echoing areas exceeding a chosen value A' would be

$$N' = N e^{-A'/\bar{A}} \qquad \text{as } N \to \infty$$

The peak echo power received from a scattering source of equivalent echoing area A at a range R from the equipment is given by

$$S = \frac{P\lambda^2 G_T G_R A}{64\pi^3 R^4}$$

where P = peak power radiated

λ = wavelength

and G_T and G_R are respectively the power gain of the transmitting and receiving aerials in the direction of the scattering source.

Consider an elementary region of space of volume δv such that the value of $\frac{G_T G_R}{R^4}$ remains sensibly constant throughout the region. Within this region $S \propto A$ therefore, and the rate of appearance of echoes of power exceeding the lower limit S' will be proportional to

$$\delta v \cdot e^{-A'/\bar{A}}$$
$$= \delta v \cdot e^{-S'/\bar{S}}$$

where $\bar{S}$ is the mean signal power received from this region.

For any given value of $\bar{A}$, and with a knowledge of the polar diagrams of the equipment and the transmitted power, we can derive the form of the variation of $S'/\bar{S}$ throughout space. By integration we may then determine the relative numbers of echoes exceeding given values of signal power.

49. The effect of this integration is to reduce the mean received signal power to a fraction of the value it would have were all the scattering sources to appear in the maximum of the beam, and also to modify slightly the signal strength distribution from the exponential form it would have in those conditions.

50. We have performed the integration for the case of a station with a vertical beam, with the simplifying assumption that all the scattering sources occurred in a single thin layer at a height of 97 km. Comparing the theoretical results with the distribution observed at the appropriate station (during June, 1945), we find that the value of A which gives closest agreement is in the neighbourhood of 430 m². The agreement between the observed distribution of echo powers and that computed by the above method is shown in Fig. 23.

51. It is to be emphasised that the choice of an exponential form of distribution is based purely on empirical grounds; also that the estimate of $430m^2$ as a mean equivalent echoing area can only be regarded as approximate. On account of the meteoric origin of the scattering sources, it is probable that the value of K will vary with the incidence of meteor streams of differing densities and velocities.

DETERMINATION OF METEOR RADIANTS

52. In Part I of the paper we pointed out that the diurnal variations in frequency of occurrence of the echoes for the oblique stations according to their direction of look could be explained in terms of aspect sensitivity of the echoing source. The meteor streak or train is an ionised column which would present the best echoing area in a direction at right angles to its axis. In this case it should be possible from the time of occurrence of the peaks in the diurnal variation to make some inferences about the main directions of travel of the meteor streams, and hence their radiants. Olivier (16) has demonstrated that minor radiants exist in very great numbers scattered all over the visible heavens, and that any radiant is not worthy of consideration if it rests on observations of more than a few days. With these facts in mind we have chosen for analysis several periods of not more than one week, and have attempted to deduce only those radiants which might account for the main peaks in the diurnal variations.

53. We shall consider first the week 6 - 13 June, 1945. The form of the hourly rate for the three stations B1, B2, and B3, on bearings 230°, 315°, and 62° respectively, is shown in Fig. 24. We note that the main peaks occur, for B1 and B2 at about 0600 hrs., and for B3 at about 1400 hrs. In Fig. 25 we have drawn the coverage of possible radiant positions in the sky for each of these stations at the time of their respective peak rates. It has been assumed that any possible radiant position is one at right angles to any part of the radio beam. From a consideration of the beam characteristics and echo strength distribution the angular dimensions of the beam likely to contain 90% of the observed echoes were computed. The coverages shown in Fig. 25 represent possible directions at right angles to any part of the beam. We notice that the coverages for the peak hourly rate of B1, B2, and B3 all intersect in a common area, and we may assume this to contain the mean radiant, R1. The position of this radiant appears to be within 10° of R.A. 58°, Decl. + 5°. If we plot the secondary peaks in the hourly rate, namely at 2030 hrs. for B1, and at 0530 hrs. for B3, in the same way we deduce a secondary radiant within about 10° of R.A. 300°, Decl. - 5°.

54. We must now verify that radiants in these positions give a satisfactory explanation of the observed hourly rate for both stations and do not introduce any additional maxima to those which are observed. The times for which these radiants are within the station coverages may readily be determined graphically, the results being tabulated below:-

Radiant	Site	Times for which radiant position is favourable. (G.M.T.)
R1 R.A. 58° Decl. +5°	B1 B2 B3	0440 - 0730 0430 - 0930 1140 - 1630
R2 R.A. 300° Decl. -5°	B1 B2 B3	2130 - 0100 2210 - 0310 0240 - 0700

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These periods have been marked below the time scale (abscissae) in Fig. 24 and they demonstrate that the radiants R1 and R2 give a satisfactory explanation of the times of the occurrence of the major and minor peaks for all three stations.

55. We shall next consider the diurnal variation of hourly rate for the period 26 July - 1 Aug., as shown in Fig. 26. The stations B1, B2, B3 are on different bearings from the ~~previous example discussed~~ above. The coverages of possible radiant positions corresponding to the marked peaks for B2 at 0230 hrs., and B3 at 0430 hrs., are shown in Fig. 27, and give a derived radiant in the neighbourhood of R.A. 330°, Decl. - 12°. In Fig. 2 we have plotted the track of the radiant across the coverages, and marked the periods below the time scale of B2 and B3. The striking agreement is made even more remarkable by consideration of B1 which exhibits a notably lower level of activity. As the coverage of this site never includes the radiant R in a favourable position, the absence of a marked peak in frequency is readily explained. The radiant R is plainly that of the δ Aquarids, a prominent stream of this epoch.

56. In the above analysis we have not included a description of the effect of the radiants on the vertical beam stations. These stations give a ring type of coverage for possible radiant positions (see Fig. 29) and many of the derived radiants considered above cross the coverage twice. (This corresponds to the rising and setting of the radiant in the sky.) This double intersection plainly tends to even out the diurnal variation of hourly rate, which is in accordance with observation. In the case of only one of the above radiants is the radiant position so placed that it remains within the coverage for the whole of the time between the rising and setting of the radiant. This is the radiant R, and its track with respect to the coverage of a vertical beam station (A1 or A2) is shown in Fig. 29. We should then expect, in this case, the vertical beam station to give a clear peak between 2100 and 0630 hrs.; comparison with Fig. 30 demonstrates that this is the case, a much clearer peak being apparent for the vertical stations than at any other time in the June - July watch.

57. An accuracy in position of better than 10° cannot be claimed for those radiants determined above. Many other minor radiants must, of course be active, but the width of the radio beams has not warranted any more detailed analysis at this stage. Further, there may be other factors which we are not in a position to assess yet, such as the optimum angle of incidence of the meteor in the ionisation layer for giving an effective radio response. Refinement of the method of observation by using narrow radio beams will undoubtedly lead to elucidation of these factors and to more accurate determination of radiants.

RELATION OF SCATTER ECHOES TO ABNORMAL E LAYER

58. We described in Part I the detailed correlation which exists between the hourly rate of occurrence of scatter echoes and meteor showers. This was demonstrated, for example, by Fig. 11 in which the peaks in frequency of occurrence of scatter echoes coincided with the Quadrantids and Lyrid showers. The correspondence is shown even more strikingly in Fig. 31 by plotting the hourly rate for broad and multiple echoes. Echoes of this type generally do not extend more than a few kilometres in range. It is of interest that during the Perseid shower of 1945 the correspondence was emphasised by plotting the long duration echoes, exceeding 5 secs. in duration, as shown in Fig. 10.

59. In view of the reports of previous workers, of increased abnormal E layer ionisation during local showers, see refs. (6), (7), (8), (9), (10), it might be expected that a correlation would exist between the hourly rate of scatter echoes and abnormal E layer critical frequencies. We have previously drawn attention to the difference in height between the

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abnormal E layer and the region of maximum frequency of occurence of scatter echoes; it does not appear permissible therefore to regard the scatter echoes merely as the densest patches of ionisation in an inhomogeneous abnormal E region. Nevertheless we might regard the abnormal E layer as a reservoir collecting residual meteoric ionisation.

60. Examination of the abnormal E critical frequency values measured by the Radio Research Board, Slough, and the Inter-Services Ionospheric Bureau, Great Baddow, has not revealed any correspondence between these values and the rate of occurence of scatter echoes during the period of our investigation. (It may be noted that the Slough and Great Baddow critical frequency values showed marked similarity, indicating that the abnormal E ionisation often extended with little difference of ionisation over this distance of about 50 miles which separated the two stations.) The absence of correlation between scatter echoes and abnormal E critical frequency is illustrated by the example shown in Fig. 32, for the period 1 - 5 January, which includes the Quadrantid shower, 3 January. We infer therefore that if the abnormal E layer [illegible] in fact receive part of its ionisation from meteors, other controlling factors, such as those discussed by Appleton and Naismith (2), were dominant in these latitudes during the present investigations. [illegible] other hand, the close relation between scatter echoes and [illegible] has been demonstrated so clearly that we conclude [illegible] factors are present their influence is [illegible].

ACKNOWLEDGEMENTS.

61. We wish to acknowledge the valu[illegible] by the [illegible] in [illegible]

[illegible]

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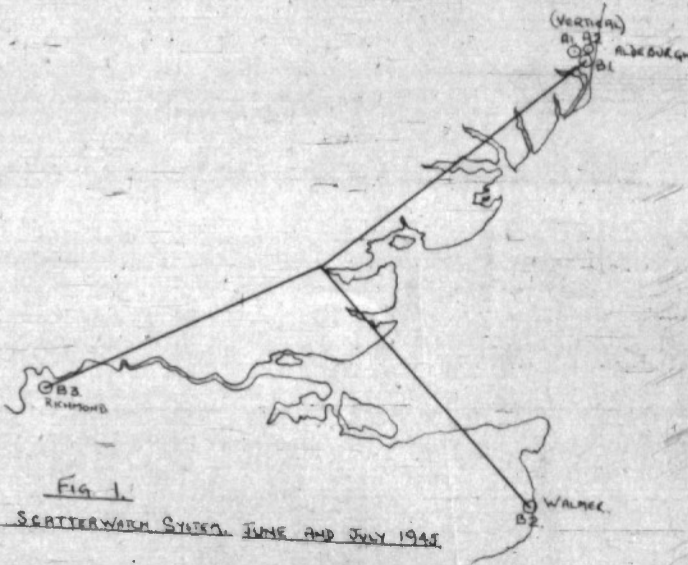
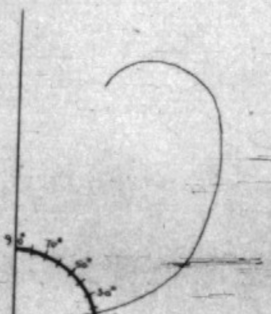


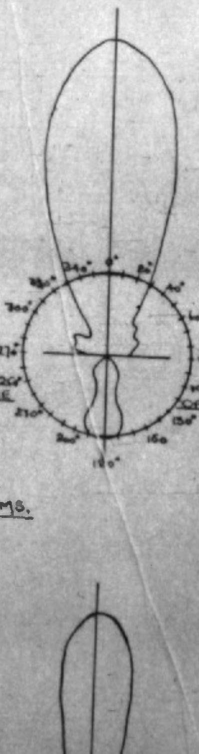
FIG 1.

SCATTERWATCH SYSTEM. JUNE AND JULY 1945

INCLINED AERIALS.



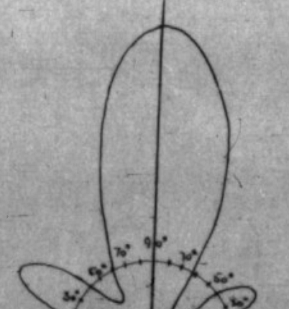
IN VERTICAL PLANE



IN PLANE OF AERIALS

FIG 2. TYPICAL POLAR DIAGRAMS.

VERTICAL AERIALS.



IN PLANE PERPENDICULAR TO DIPOLES

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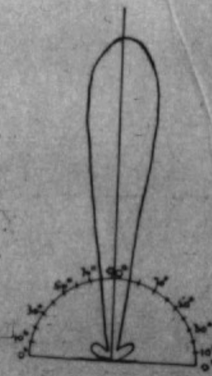
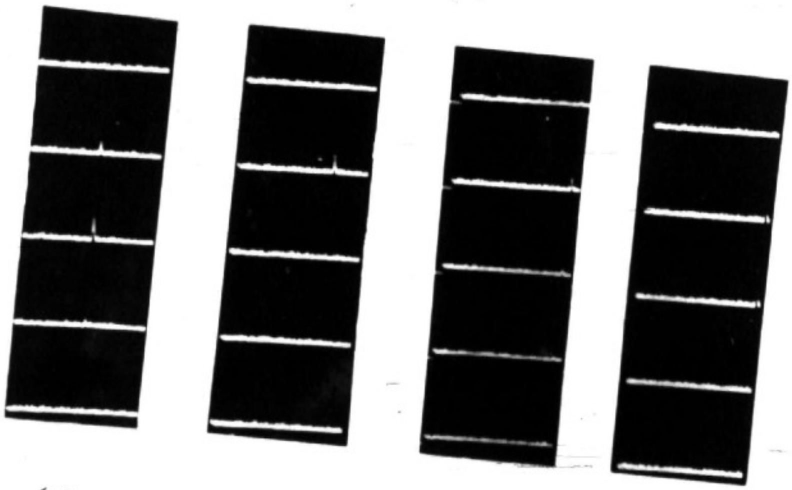


IN PLANE OF DIPOLES



(a) (b) (c) (d)

Fig. [illegible]

Cine photographs of scatter echoes (16 frames/sec.)
Timebase range limits 80 - 125 Km.

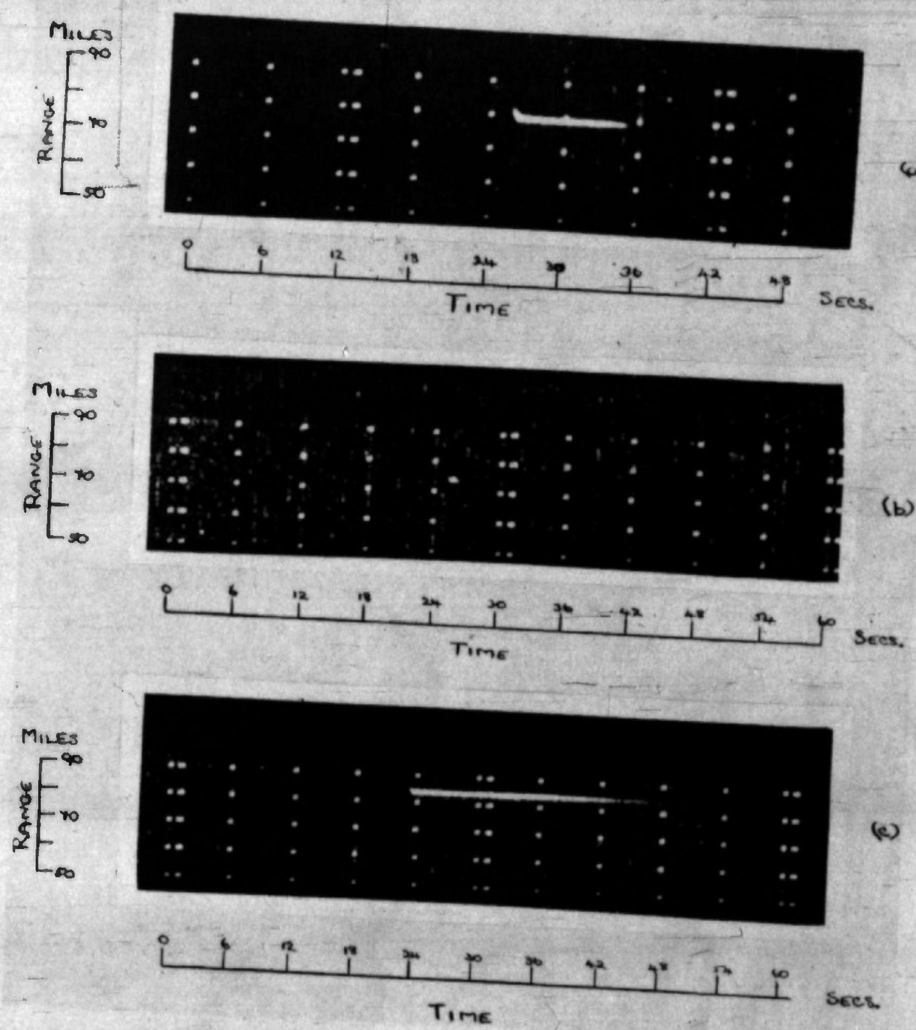


Fig. 4

Photographic records of scatter echoes.

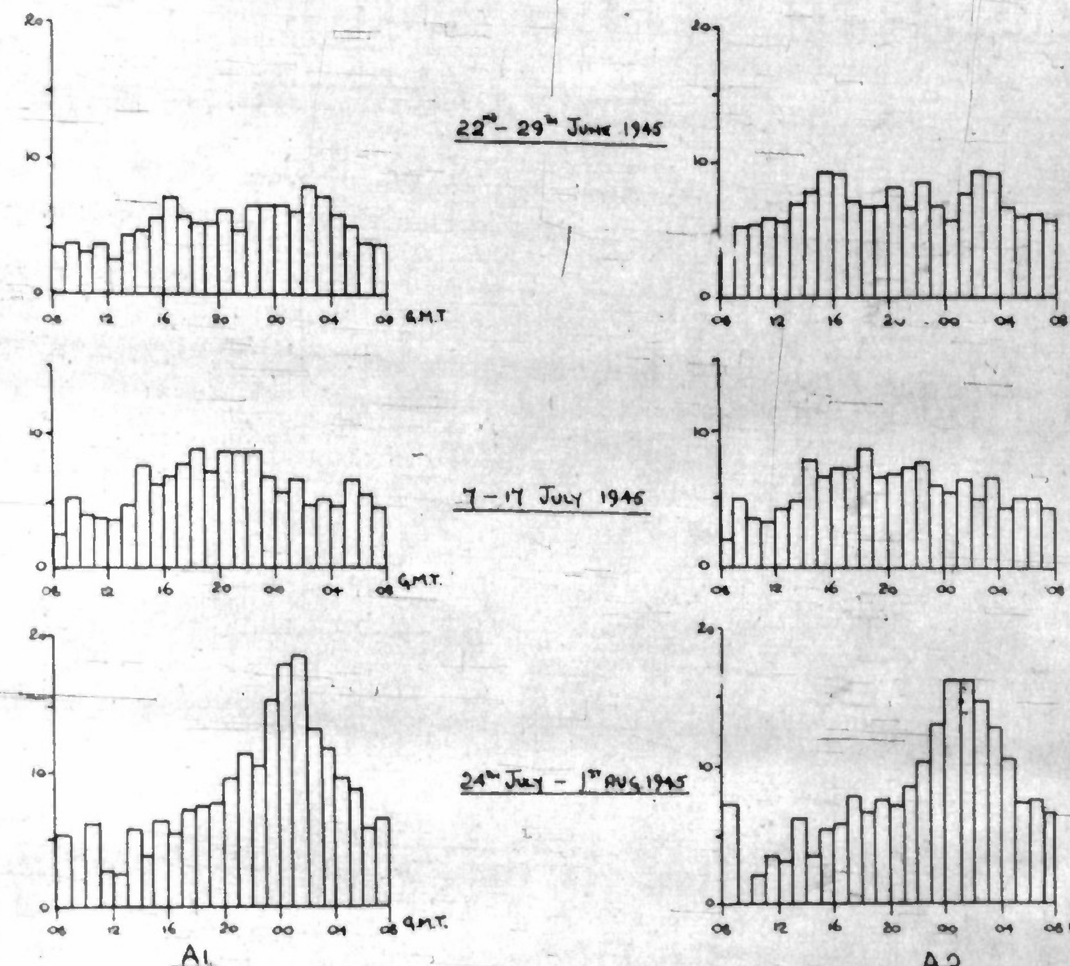


Fig 5

DIURNAL VARIATIONS IN HOURLY RATE OF OCCURANCE OF ECHOES.

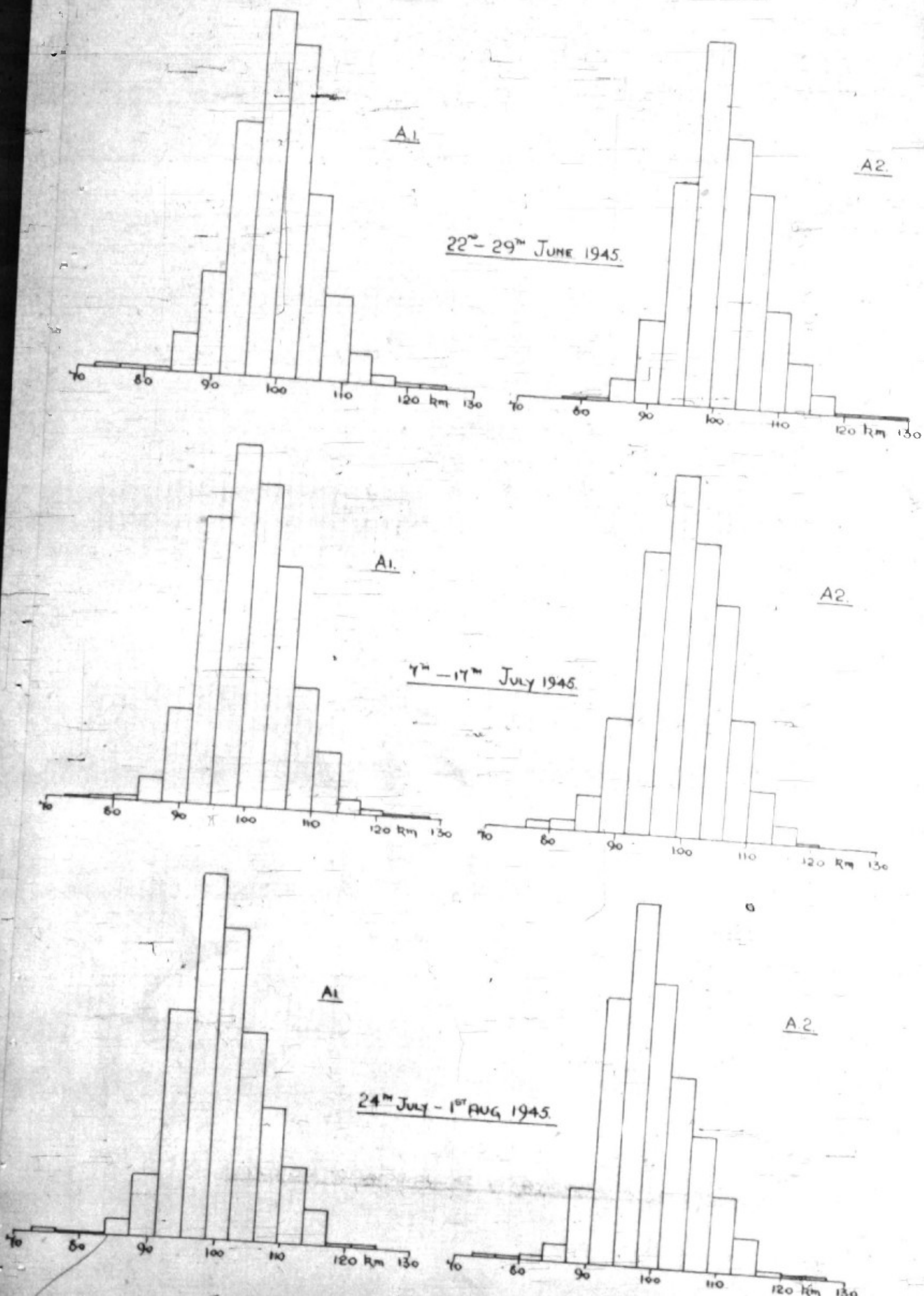


Fig. 6. RANGE DISTRIBUTION OF SCATTER ECHOES.

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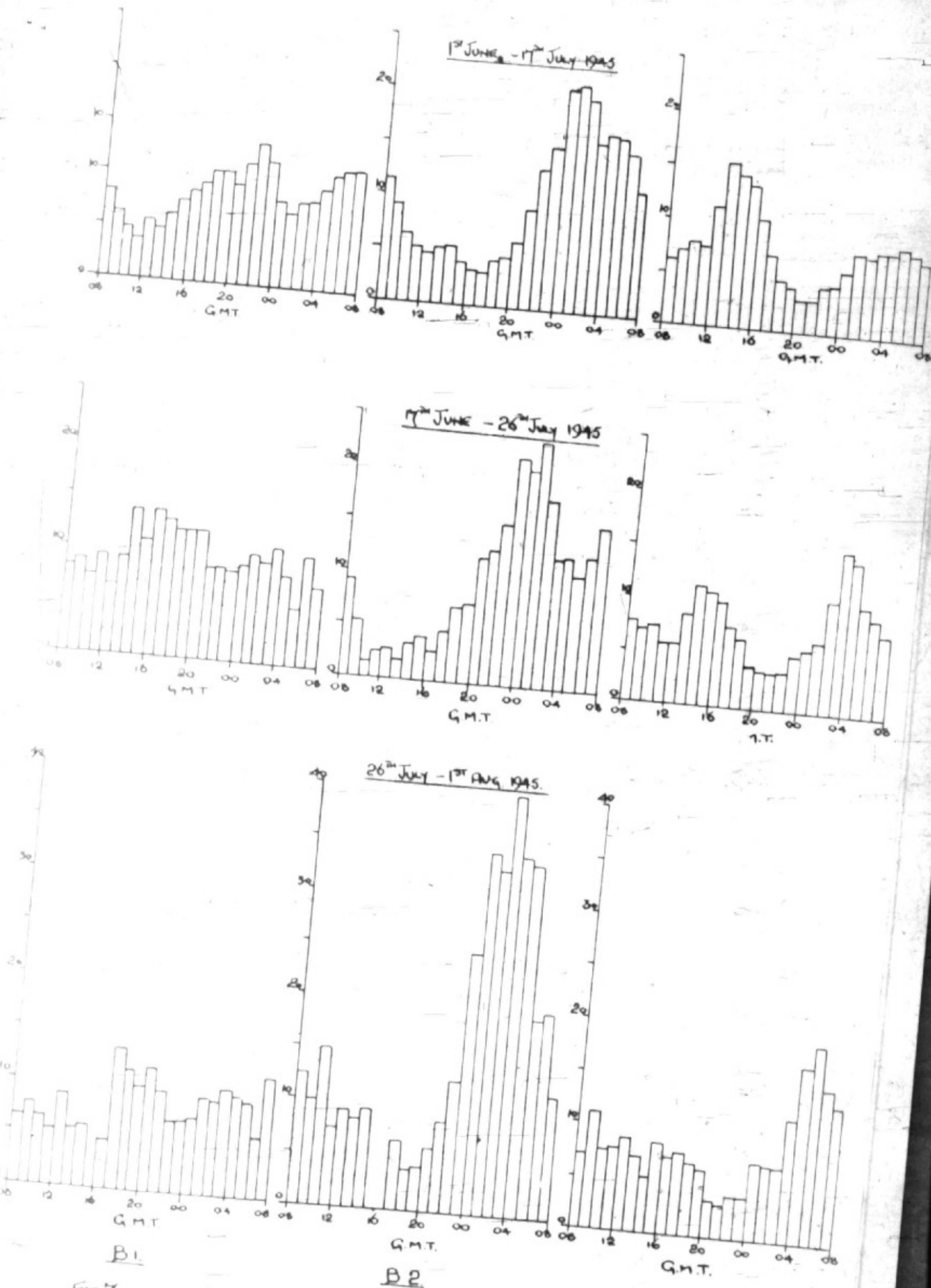

Fig 7 DIURNAL VARIATIONS IN HOURLY RATE OF OCCURANCE OF ECHOES.

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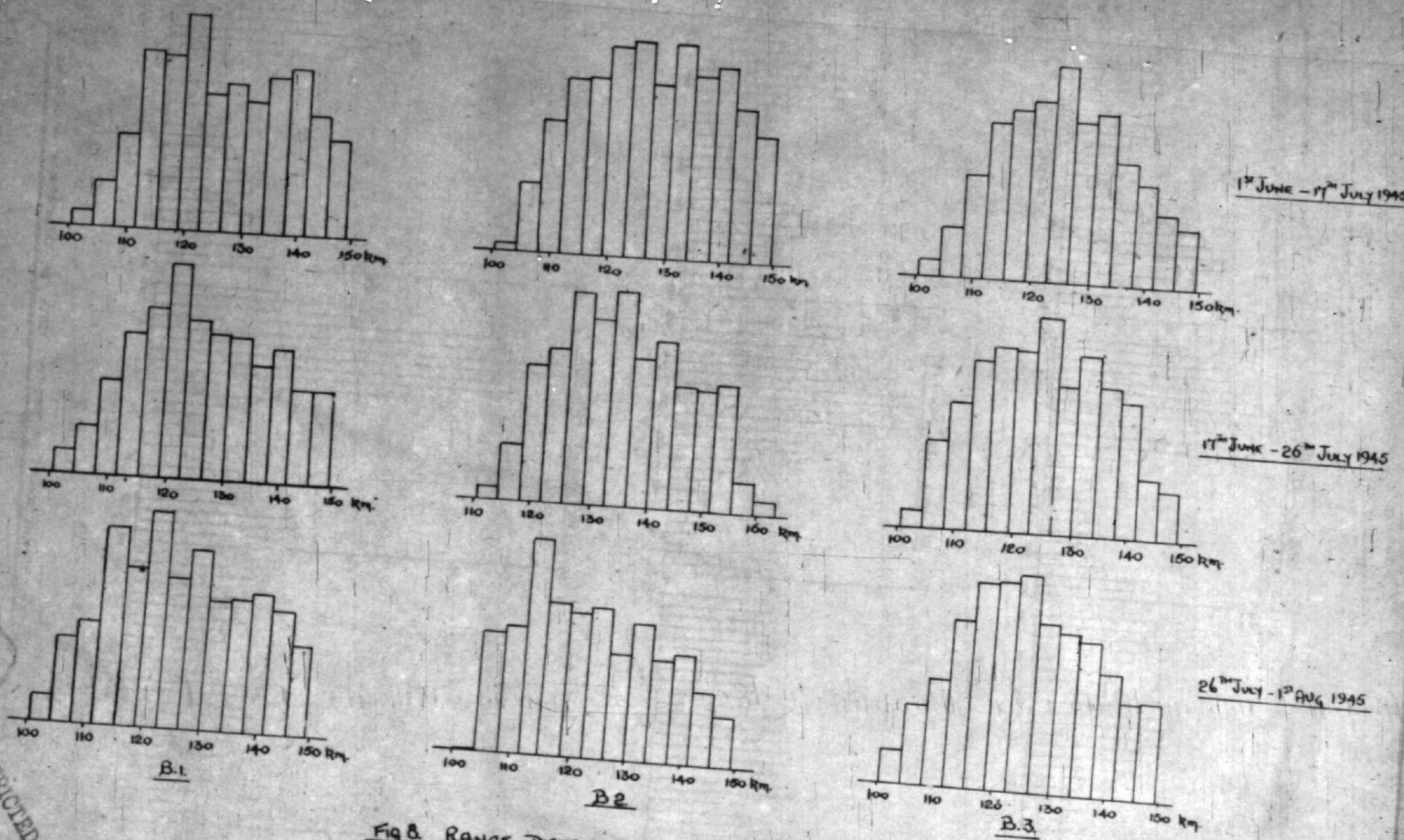

Fig 8. Range Distribution of Scatter Echoes.

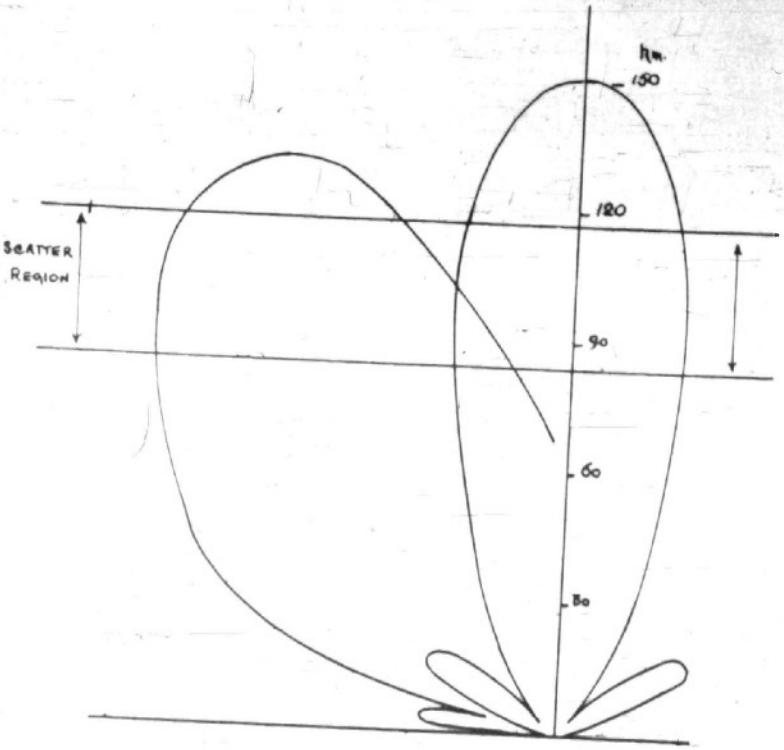

Fig 9 (a)

ILLUSTRATING OVERLAPPING BEAMS OF VERTICAL AND INCLINED AERIALS.

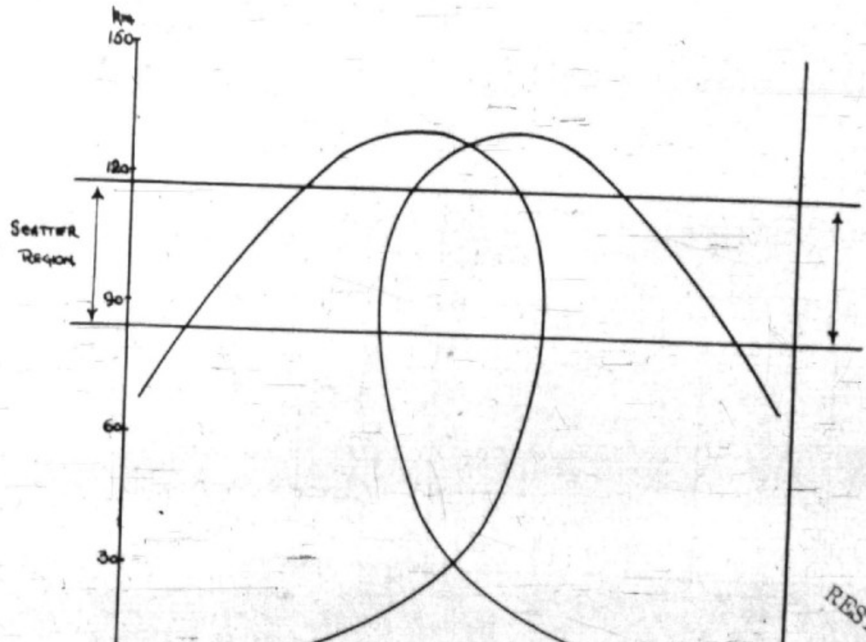

Fig 9 (b).

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ILLUSTRATING OVERLAPPING BEAMS OF INCLINED AERIALS.

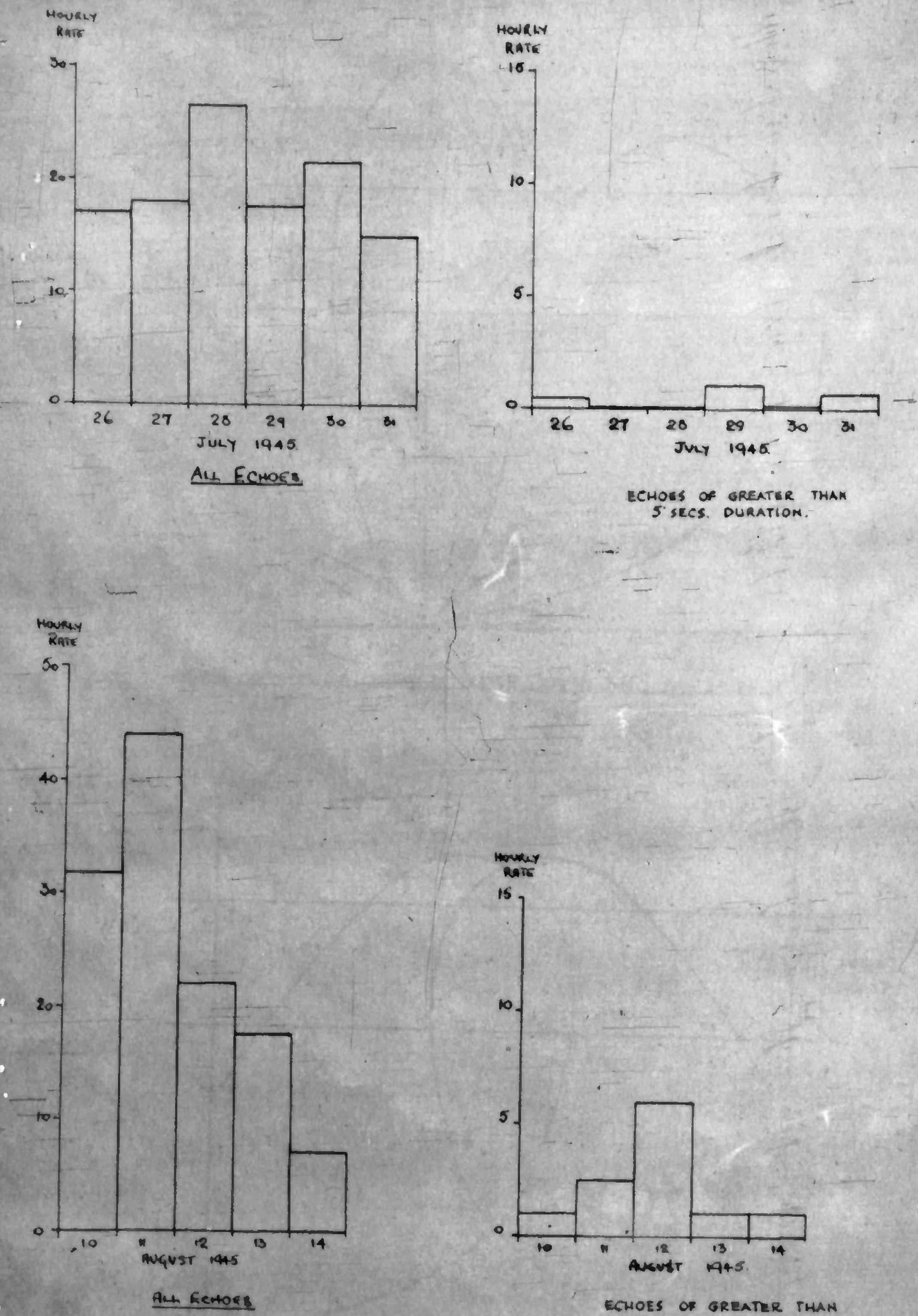

Fig 10 FREQUENCY OF OCCURRENCE OF SCATTER ECHOES

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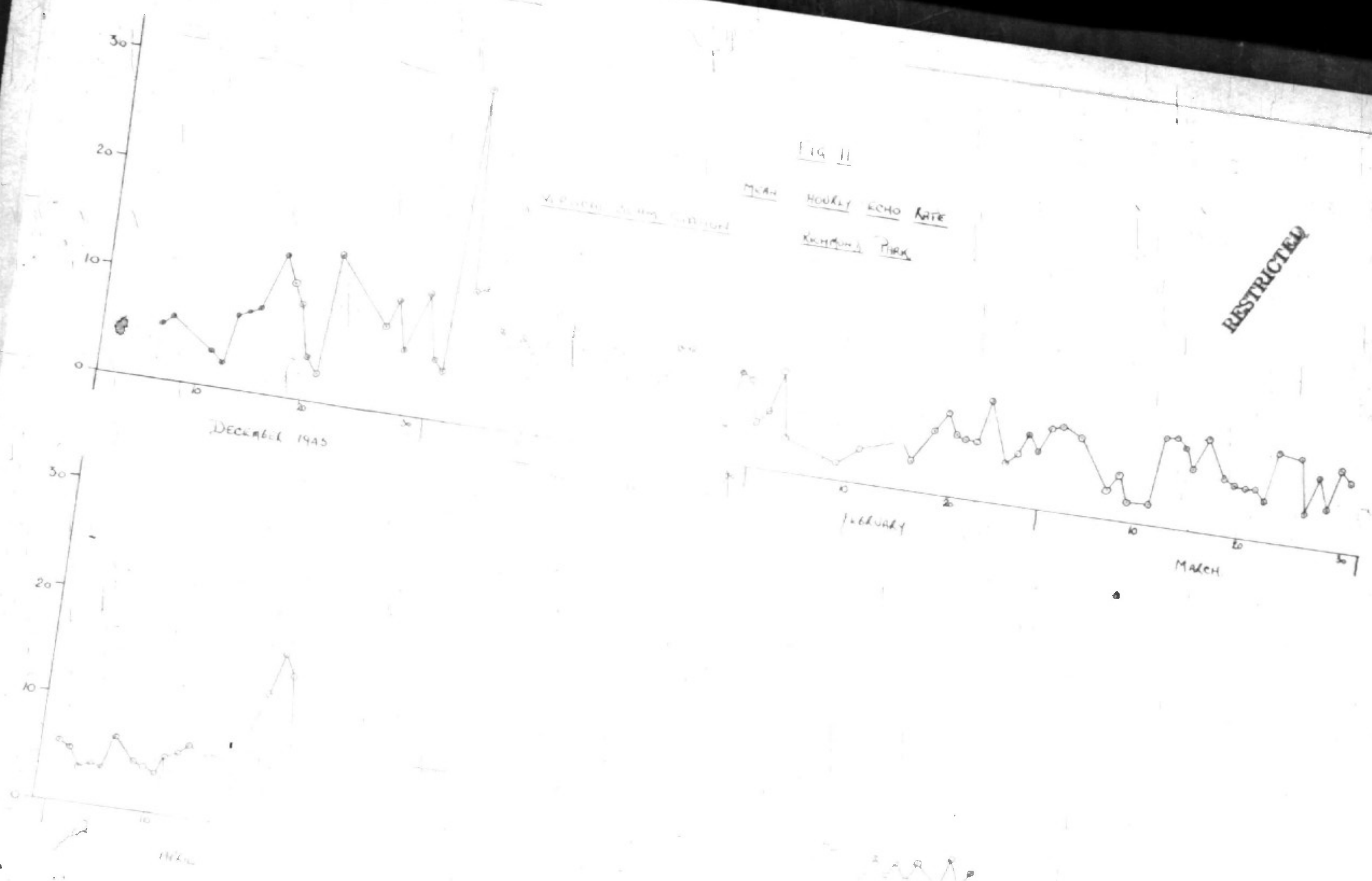
FIG 11

MEAN HOURLY ECHO RATE

RICHMOND PARK



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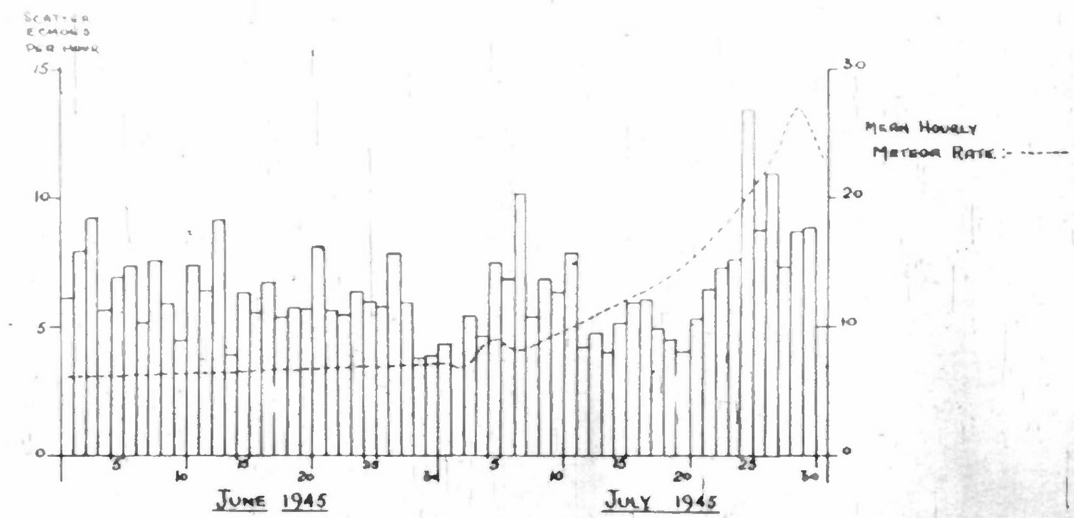

FIG 12 HOURLY RATE OF SCATTER ECHOES A1 AND A2 (VERTICAL BEAMS)

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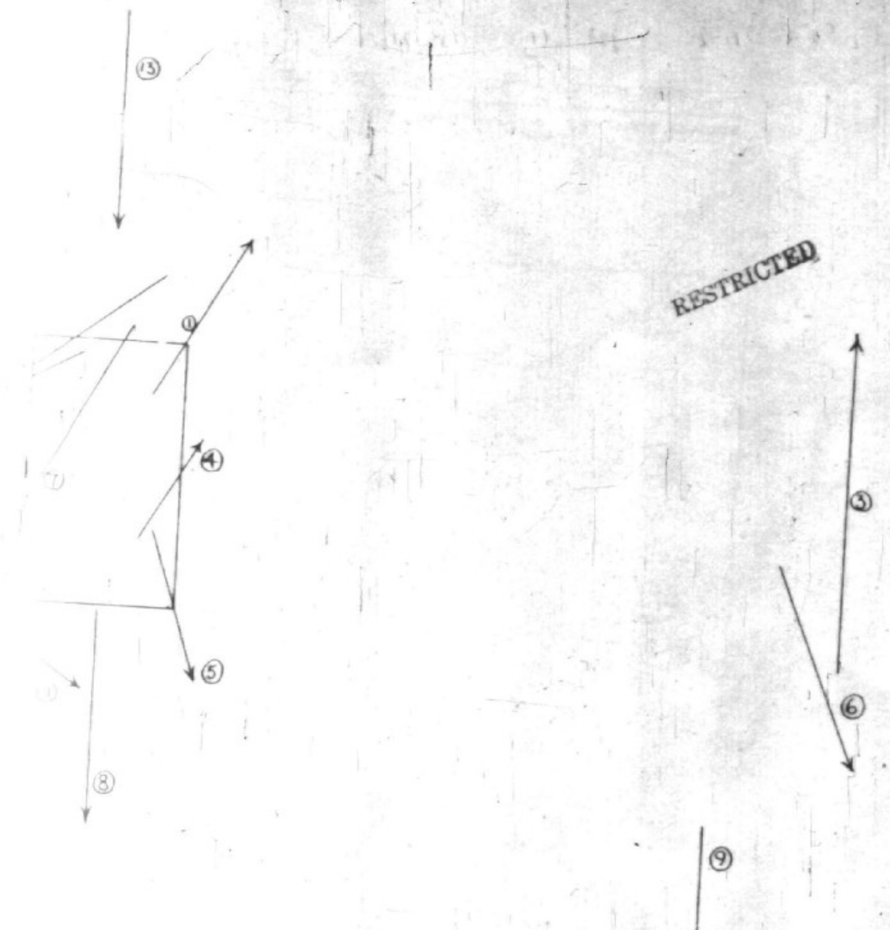

METEORS OBSERVED — SCATTER WATCH 1946. (APRIL 20th-22nd)

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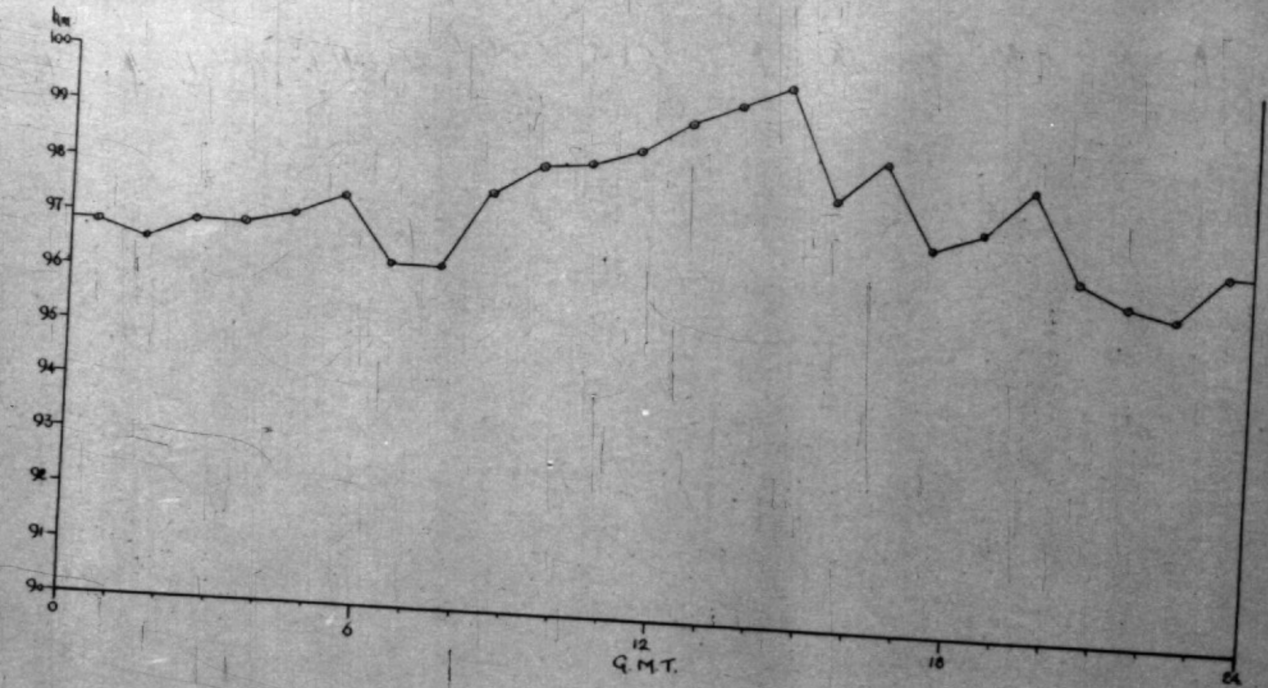

FIG. 14. DIURNAL VARIATION IN RANGE OF REGION OF MAXIMUM DENSITY OF SCATTER ECHOES.
AVERAGE OF RESULTS FOR VERTICAL BEAM STATIONS DURING JUNE AND JULY 1945

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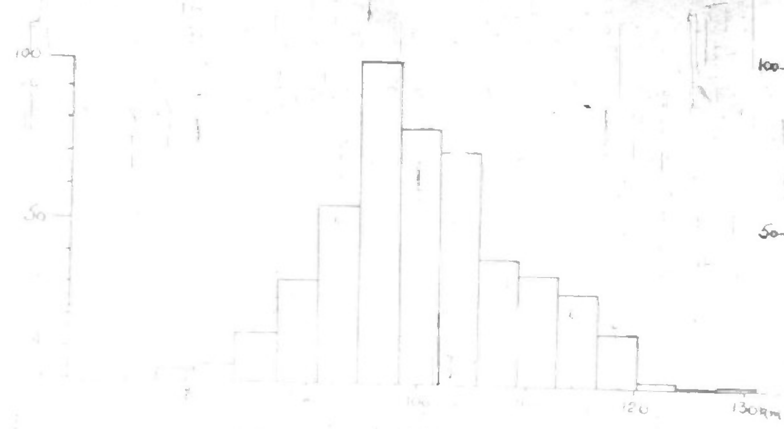

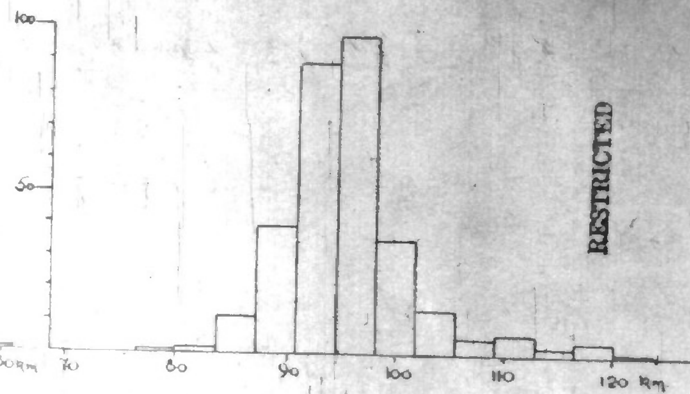

1st FEB 1946 - 30th MAR 1946

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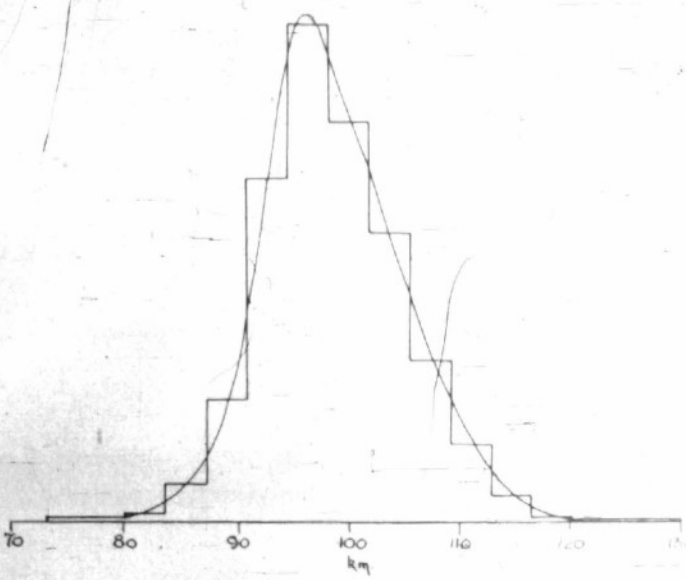

FIG. 16 MEAN RANGE DISTRIBUTION of ECHOES FOR VERTICAL BEAM STATIONS

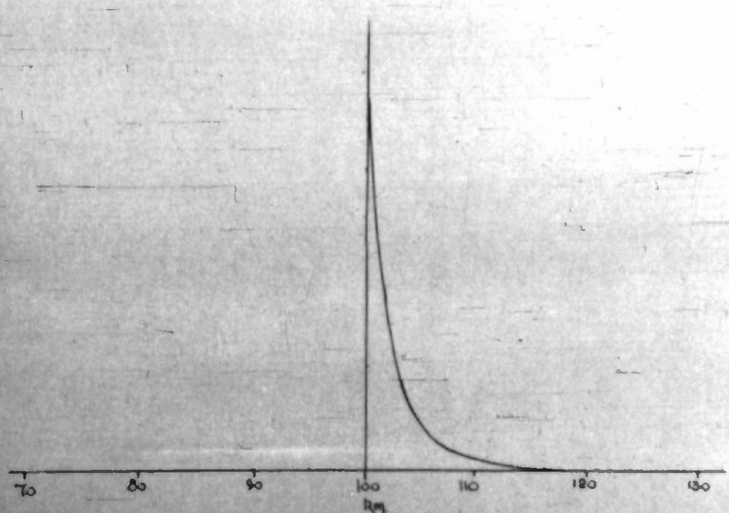

FIG. 17 EXPECTED RANGE DISTRIBUTION of ECHOES from a THIN LAYER at 100 km HEIGHT SHOWING EFFECT of RADAR BEAM

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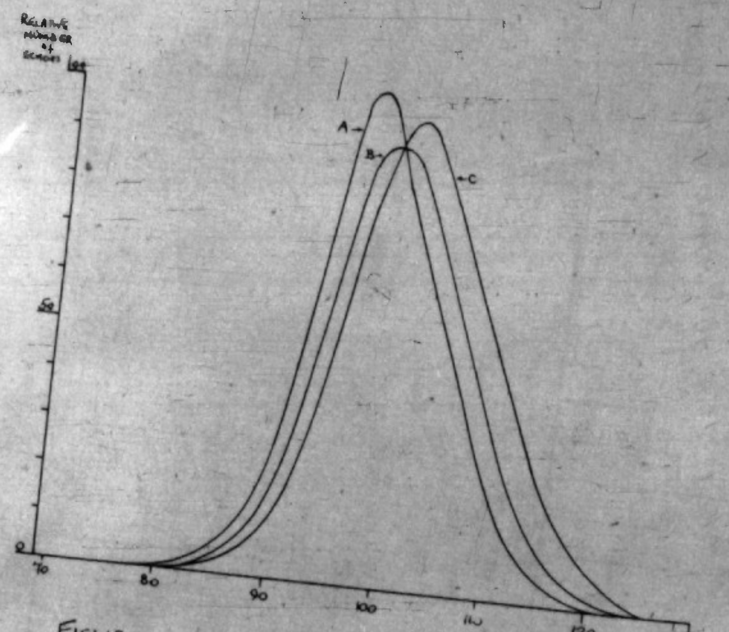

FIG: 18 ILLUSTRATING METHOD of DERIVING HEIGHT DISTRIBUTION

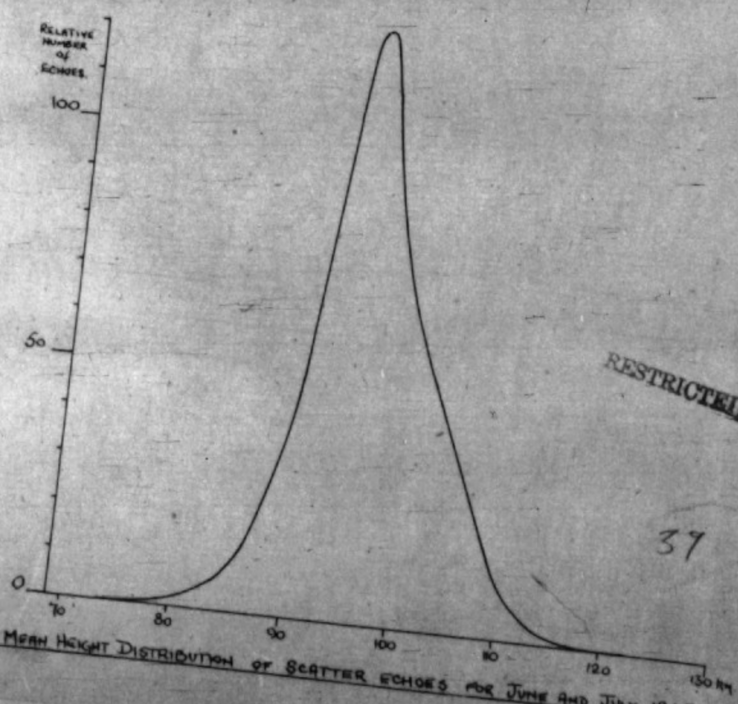

FIG 19. MEAN HEIGHT DISTRIBUTION OF SCATTER ECHOES FOR JUNE AND JULY 1945.

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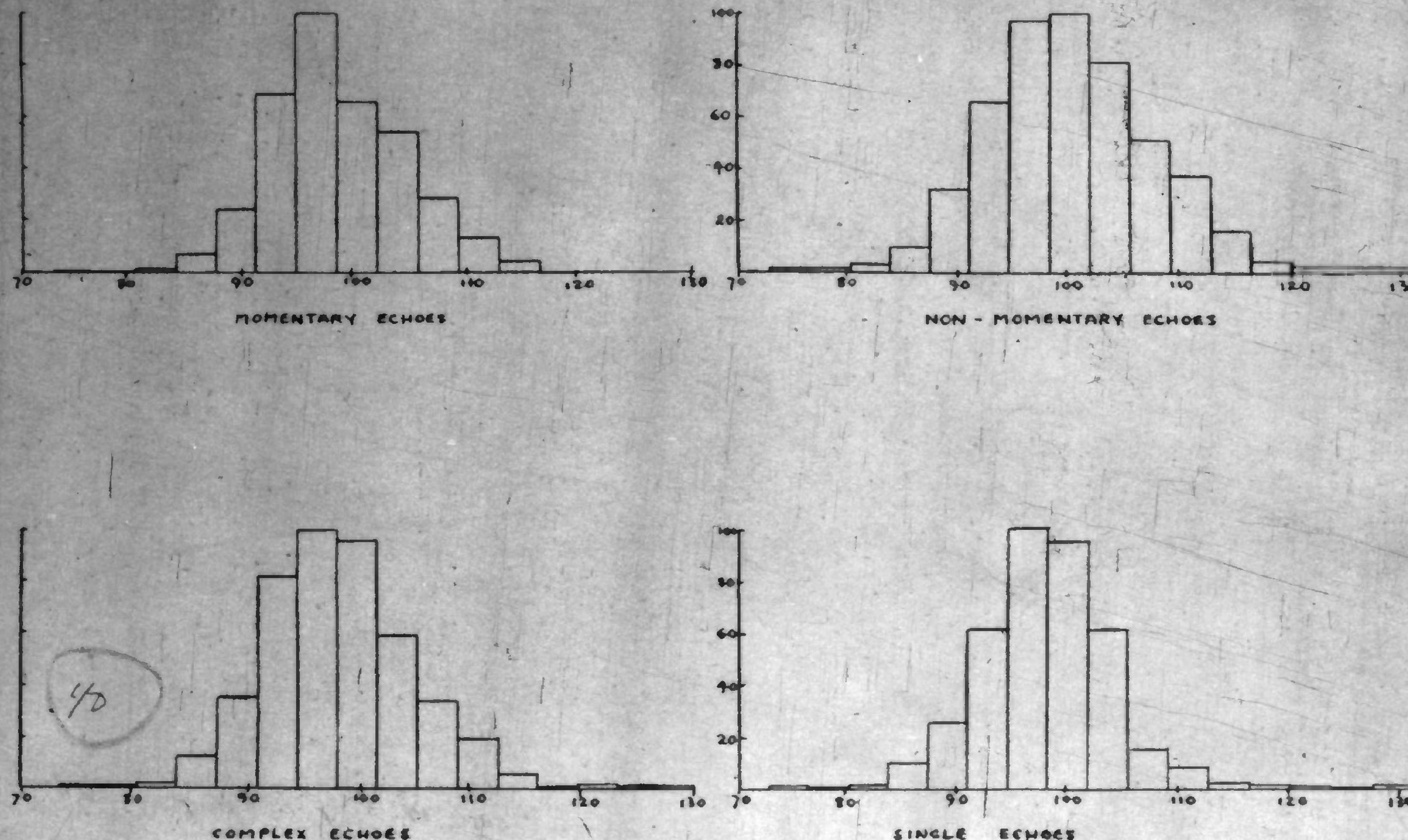

FIG 20: RANGE DISTRIBUTIONS OF NUMBERS OF ECHOES OF DIFFERENT CHARACTERISTICS:
VERTICAL BEAM STATION JUNE AND JULY 1946.

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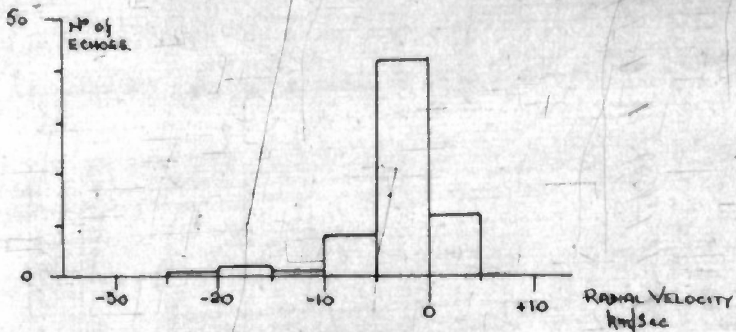

FIG 21

DISTRIBUTION of RADIAL VELOCITY of MOVING ECHOES of DURATION > 1/2 SEC. VERTICAL BEAM STATION A2 JULY 1945

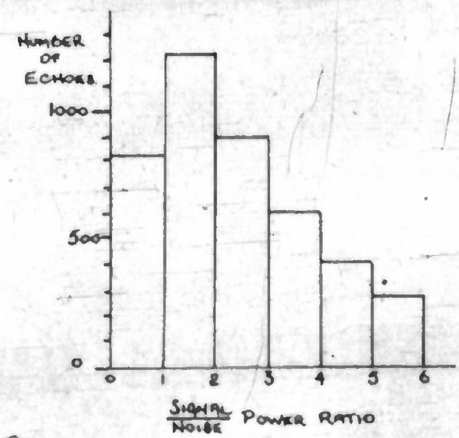

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FIG. 22 EXPERIMENTAL ECHO POWER DISTRIBUTIONS VERTICAL BEAM STATION A2. JUNE AND JULY 1945.

NOTE :- NO EXPERIMENTAL MEASUREMENTS ABOVE S/N ·6

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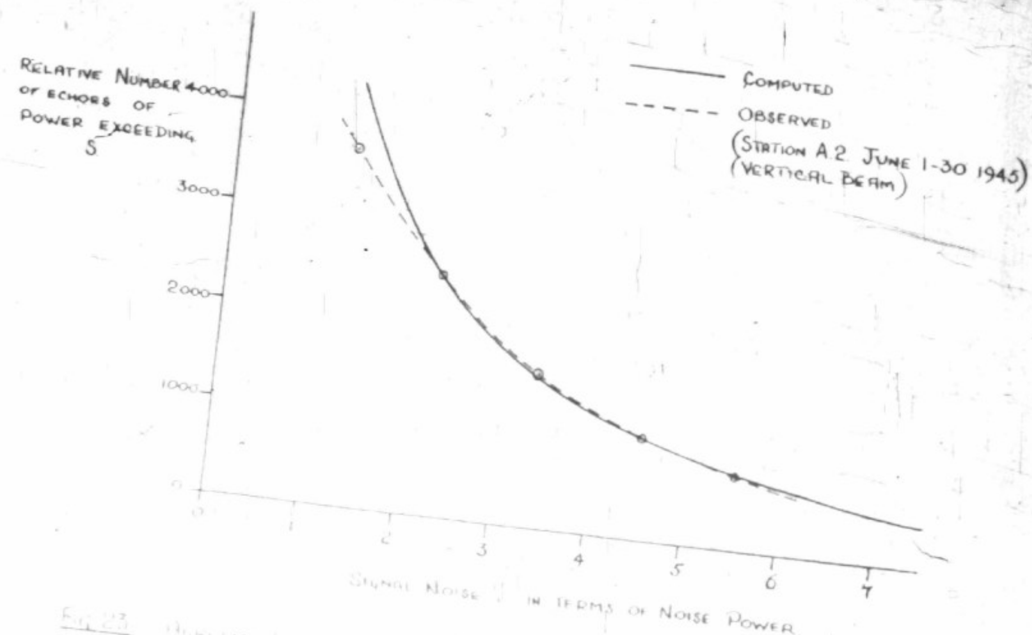


Fig. [illegible] Agreement Between Computed and Observed Forms of [illegible] Assumed Mean Equivalent [illegible]

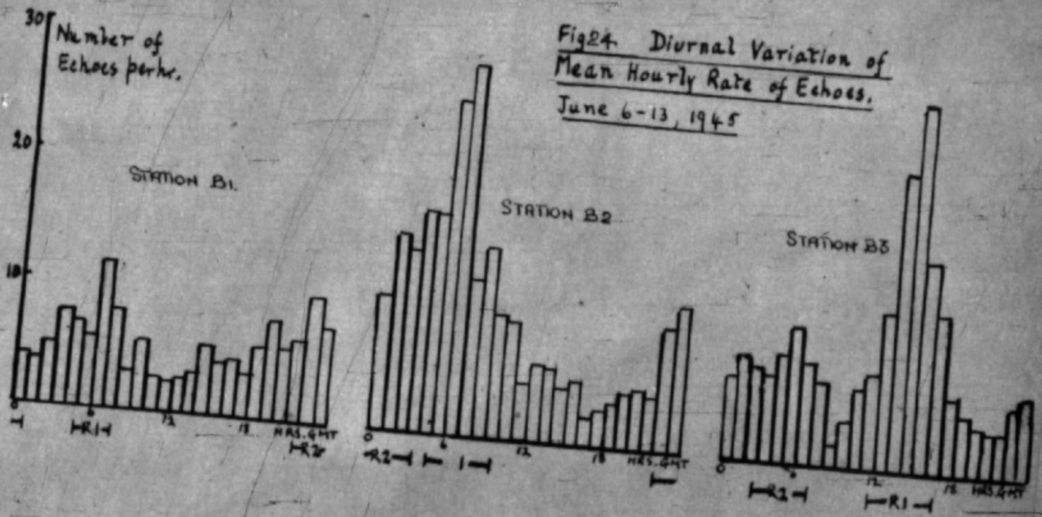
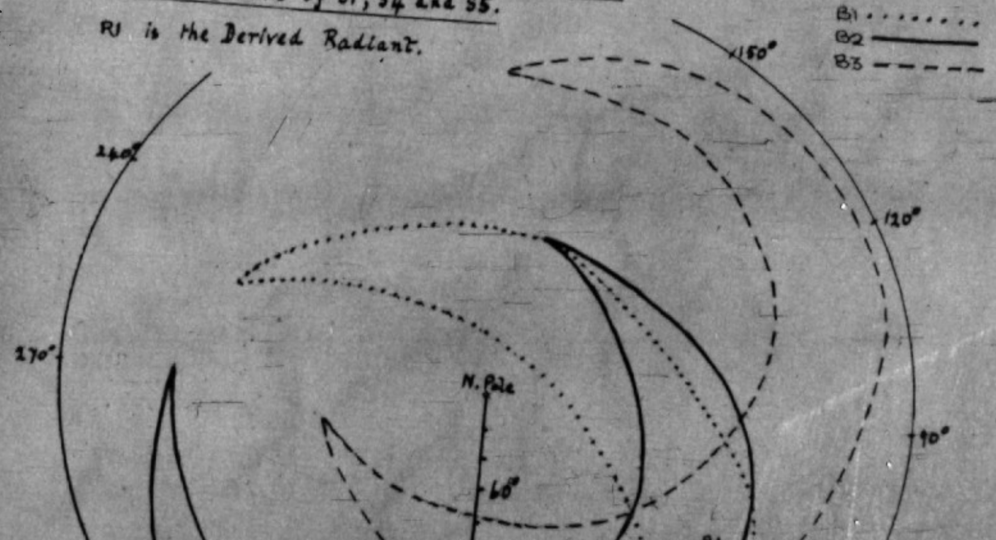


Fig 24. Diurnal Variation of Mean Hourly Rate of Echoes. June 6-13, 1945

Fig 25. Coverage of Possible Radiant Positions for Main Peaks of S1, S4 and S5.

R1 is the Derived Radiant.



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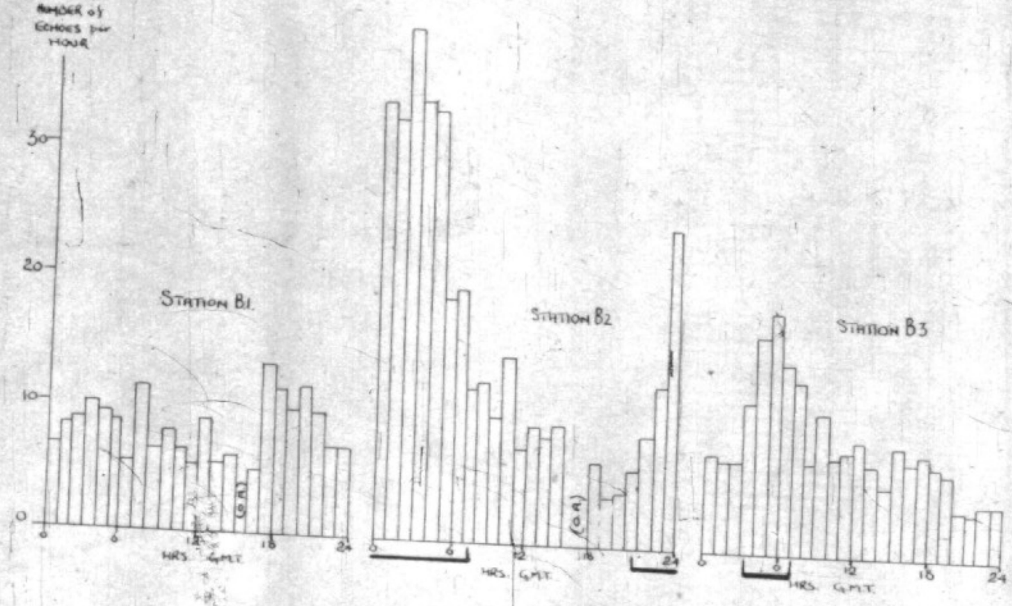

Fig. 26 DIURNAL VARIATIONS of MEAN HOURLY RATE of ECHOES 26th JULY - 1st AUGUST 1945

TIMES AT WHICH THE RADIANT (R.A 345°, DECL. -10°) IS FAVOURABLE ARE INDICATED BY HEAVY LINES

(O.A. : OUT OF ACTION)

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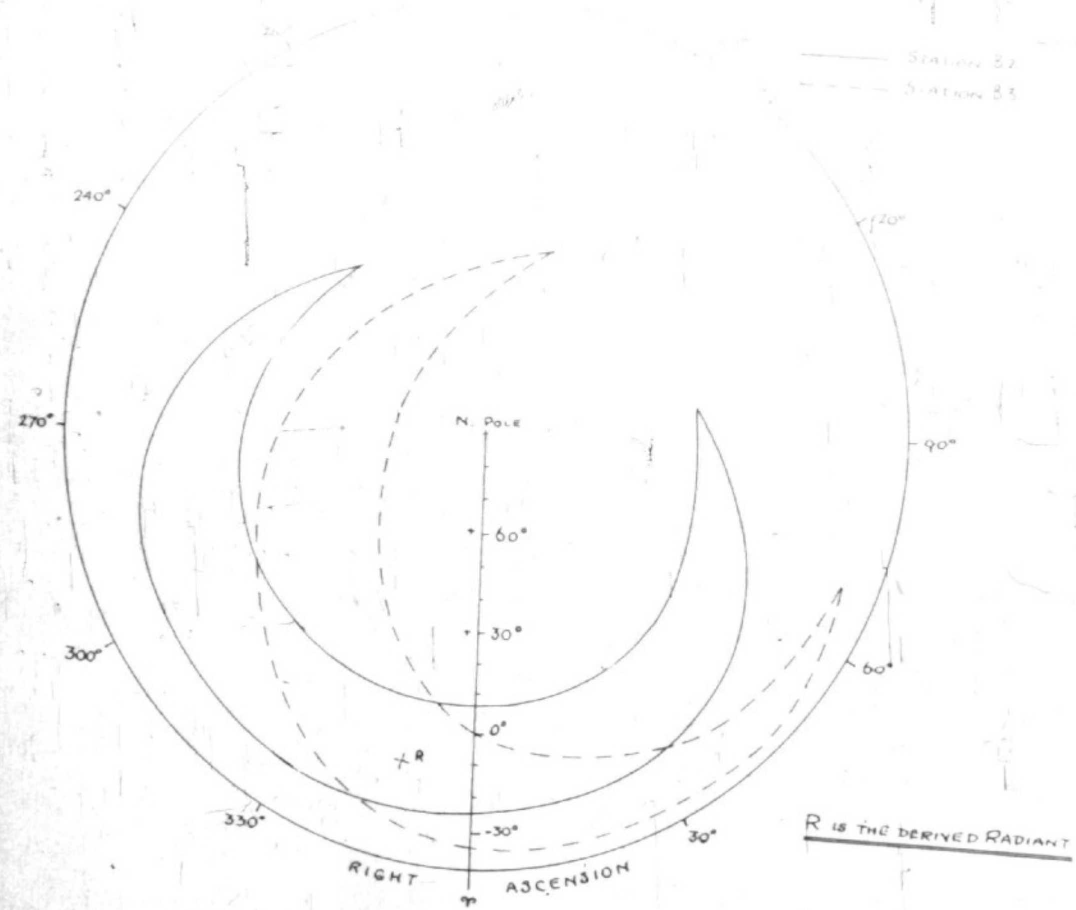

Fig 27 Coverage of Possible Radiant Positions for Main Peaks of Stations B2 and B3

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FIG. 28. TRACKS (DOTTED LINE) OF METEOR RADIANT R WITHIN COVERAGES OF STATIONS B2 AND B3.

TIME IN HOURS G.M.T. MARKED ON TRACKS.

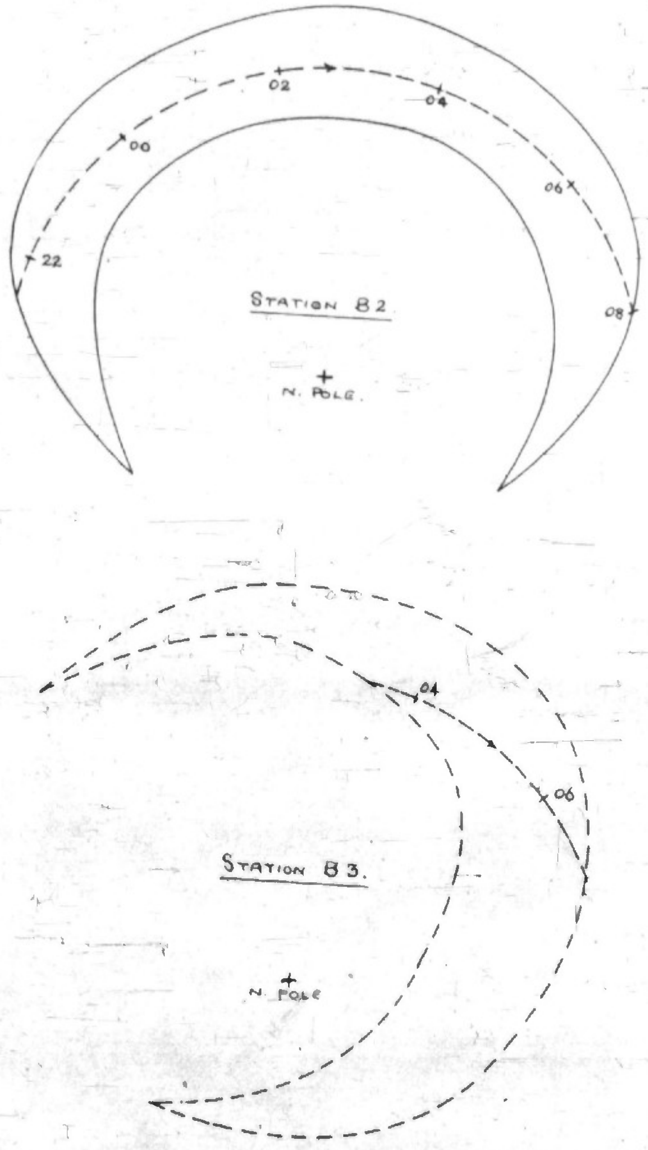

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Fig 29

TRACK (DOTTED LINE) OF METEOR RADIANT WITHIN COVERAGE OF VERTICAL BEAM STATIONS A1. A2.

TIME IN HOURS G.M.T. MARKED ON TRACK

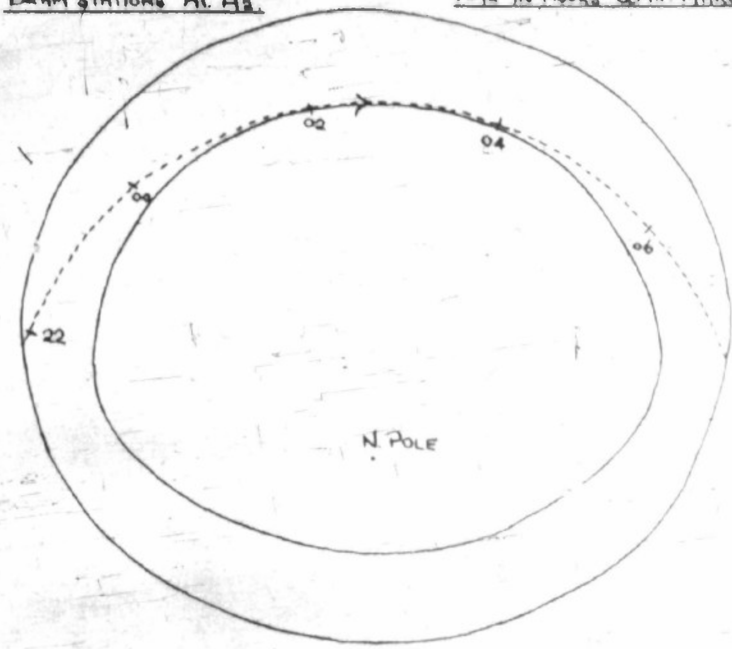

Fig 30.

DIURNAL VARIATION OF MEAN HOURLY RATE OF ECHOES FOR VERTICAL BEAM STATION A1. 26 JULY - 1 AUGUST 1945

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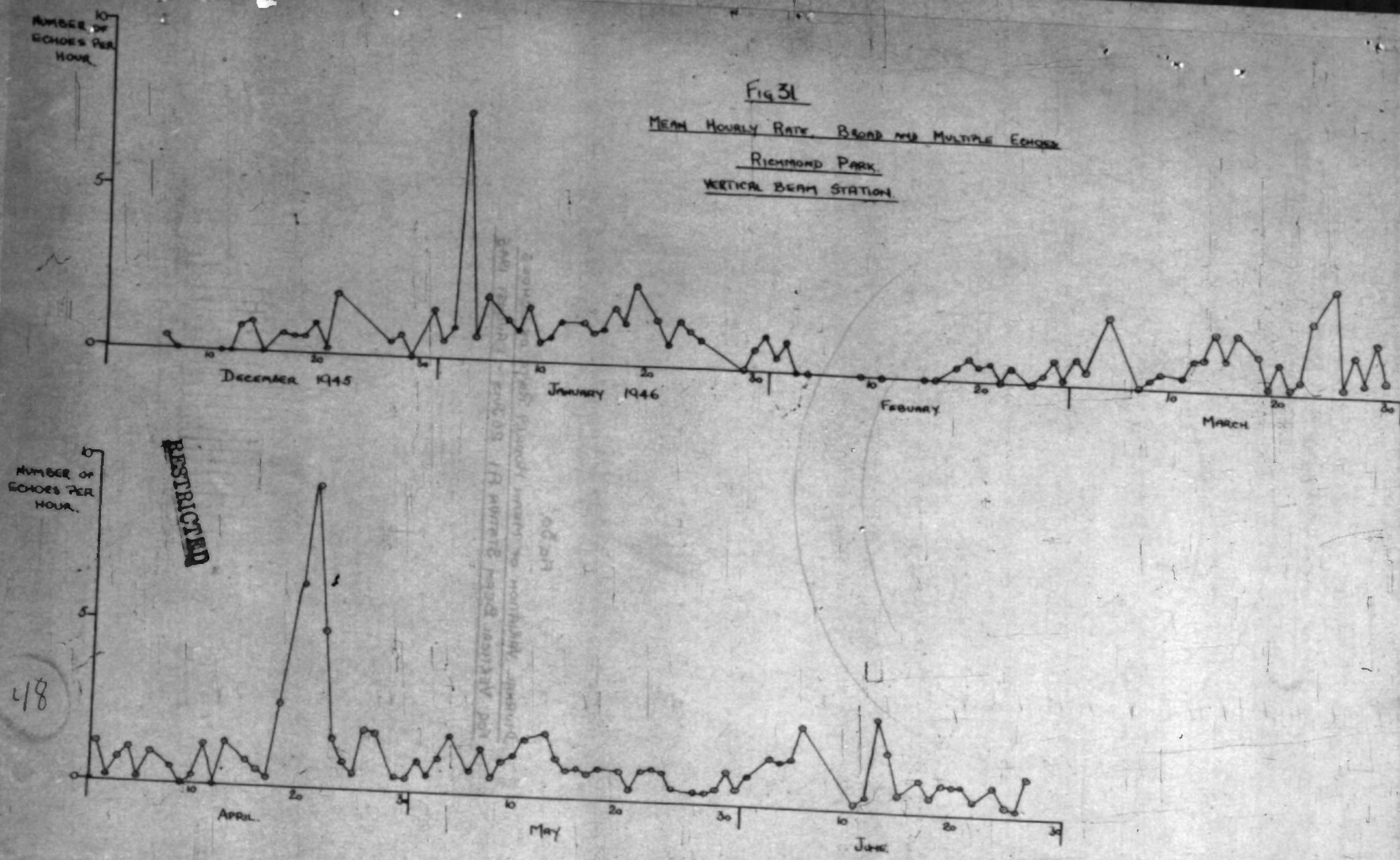

Fig 31

MEAN HOURLY RATE. BROAD AND MULTIPLE ECHOES

RICHMOND PARK

VERTICAL BEAM STATION

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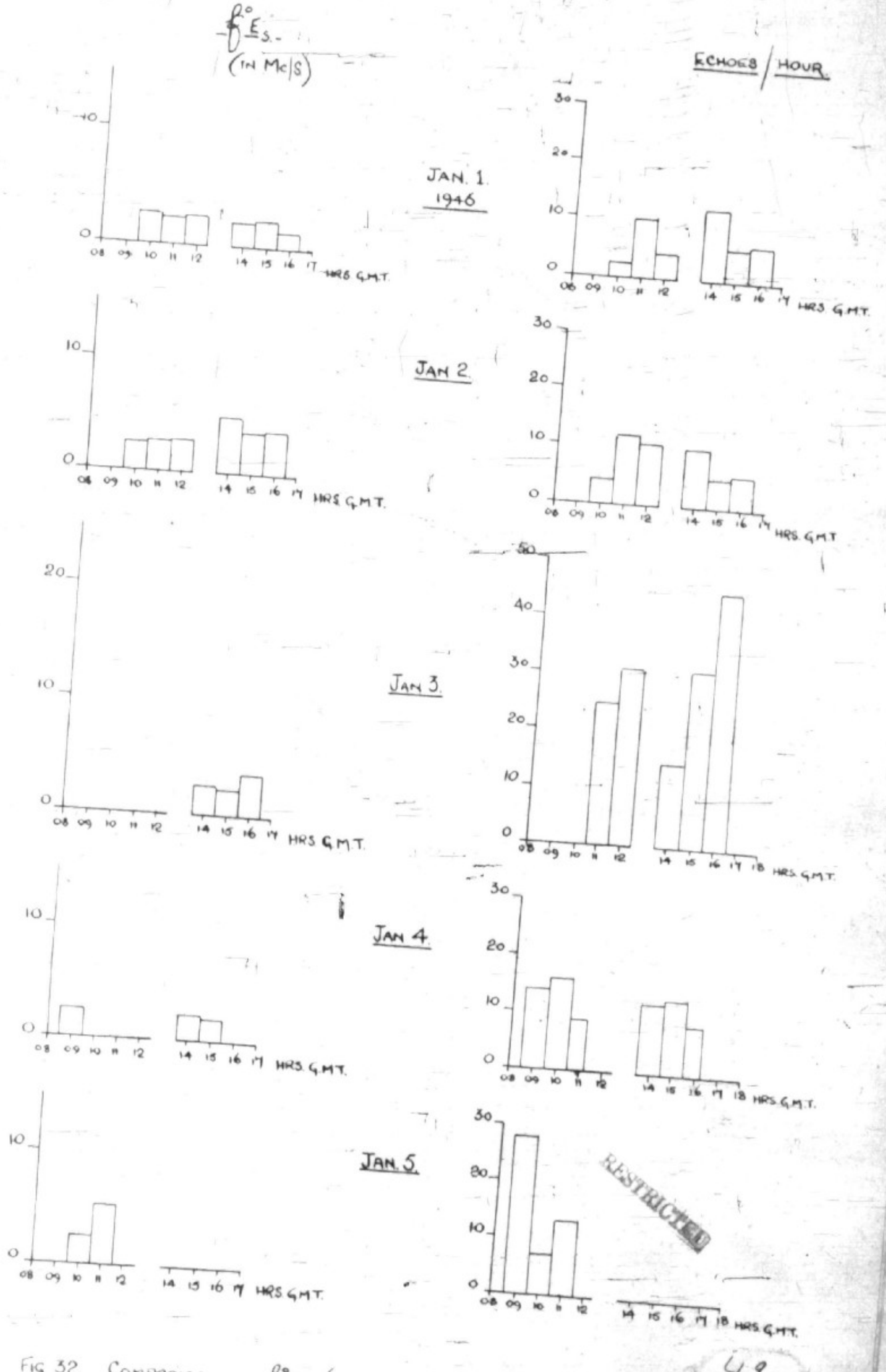

FIG. 32. COMPARISON OF $f^\circ E_s$ (GREAT BADDOW) AND NUMBER OF SCATTER ECHOES PER HOUR (VERTICAL BEAM, RICHMOND PARK)

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ABSTRACT:

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